Impact de la stimulation multisensorielle et des cybermalaises sur la présence en contexte d’anxiété en réalité virtuelle

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Thèse soumise à l’Université d’Ottawa

dans le cadre des exigences du programme de

doctorat en psychologie expérimentale

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Préface

Cette thèse comprend une introduction générale, trois articles, une discussion générale et une conclusion. L'introduction générale présente des concepts importants dans le domaine de la réalité virtuelle (RV). Le premier article, *A novel integrated information processing model of presence*, propose un modèle conceptuel sur l'intégration multisensorielle et la présence en RV. Le deuxième article, *Exploring self-reported and behavioral presence in a context of anxiety using a virtual sliding door paradigm*, porte sur une étude expérimentale comparant une mesure auto-rapportée et une mesure comportementale pour évaluer la présence en contexte d'anxiété. Le troisième article, *Exploring the relationship between presence, anxiety, and cybersickness in a virtual environment involving heights*, présente une étude expérimentale explorant la relation entre la présence, les cybermalaises et la stimulation multisensorielle en contexte d'anxiété. Finalement, la discussion générale et la conclusion résument les principaux résultats et les limites des deux études expérimentales et proposent des directions futures pour la recherche.

Les Comités d'éthique de la recherche de l'Université du Québec en Outaouais (#2021-1359) et de l'Université d'Ottawa (#H-03-21-6772) ont approuvé les deux études expérimentales. Les participants ont signé un formulaire de consentement avant de participer aux études, ainsi qu'un formulaire de débriefing après celles-ci. L'auteure de la thèse a mené la recension des écrits, la collecte et l'analyse des données et a rédigé les trois articles. L'auteure et le superviseur de thèse ont conçu la méthodologie des études. Une équipe technique a développé les environnements virtuels, des assistantes de recherche ont aidé avec la collecte de données et les co-auteurs des articles ont contribué à l'analyse des données et la révision des articles. La permission écrite de la revue a été obtenue (voir l'Annexe A) pour reproduire le premier article (voir Chapitre 2) dans la thèse. Les deuxième et troisième n'ont pas encore été publiés.

Résumé

La présence, l'illusion perceptuelle « d'être là » dans l'environnement virtuel, constitue une composante essentielle de la réalité virtuelle (RV). Selon Slater, la présence a deux composantes : l'illusion de place et l'illusion de plausibilité. Les mesures auto-rapportées sont couramment utilisées pour mesurer la présence en RV, mais elles sont souvent administrées après les immersions et n'évaluent pas le comportement des utilisateurs en RV. Il s'avère donc nécessaire d'utiliser des mesures comportementales pour évaluer la présence, surtout dans des environnements virtuels anxiogènes, qui sont utilisés dans plusieurs domaines.

Des études antérieures ont montré que l'anxiété et la stimulation multisensorielle influencent la présence. Cependant, le rôle des mécanismes d'intégration multisensorielle sur la présence, particulièrement dans un contexte émotionnel, reste peu étudié. Le deuxième chapitre de la thèse a exploré ce sujet plus en profondeur et a proposé un modèle conceptuel de la présence. Deux études expérimentales ont ensuite examiné la relation entre la présence, l'anxiété et la stimulation multisensorielle en contexte d'anxiété. L'objectif principal était d'évaluer une mesure comportementale de la présence, tout en documentant la convergence entre les mesures subjectives et objectives de la présence. Cette mesure, inspirée d'études antérieures, implique que les participants pivotent physiquement leurs épaules pour traverser des portes étroites en RV.

La première étude expérimentale (n = 25) a évalué la méthodologie afin de valider les environnements virtuels et la mesure comportementale de la présence en contexte émotionnel. Les participants ont été exposé à trois conditions expérimentales : (1) Contrôle, (2) Risque de tomber et (3) Risque de tomber + Feu. Durant les immersions, les participants ont physiquement marché sur une planche virtuelle et traversé les portes virtuelles étroites. Les deux conditions avec le risque de tomber comprenaient une fosse profonde virtuelle. Avant et après les immersions, les participants ont rempli plusieurs questionnaires. Les résultats ont révélé une corrélation non significative entre les mesures auto-rapportées et comportementales de la présence, ainsi qu'une différence non significative entre les conditions expérimentales en termes d'anxiété. Toutefois, des résultats inattendus ont indiqué que la présence et les cybermalaises auto-rapportés, ainsi que l'anxiété et les cybermalaises, étaient significativement corrélés.

La deuxième étude expérimentale (n = 25), une continuation de la première étude, a apporté des modifications au protocole expérimental et à l'environnement virtuel afin d'augmenter la présence et l'anxiété. Ensuite, de manière semblable à la première étude, l'étude a évalué la mesure comportementale de la présence en contexte d'anxiété. À la suite des résultats inattendus liés aux cybermalaises, l'étude a également exploré la relation entre la présence, l'anxiété, les cybermalaises et la stabilité posturale à l'aide de la mesure comportementale, des questionnaires et des plateformes de force. Les participants ont été exposés à deux conditions expérimentales, plutôt que trois : (1) Contrôle et (2) Risque de tomber. Les résultats étaient semblables à la première étude et ont révélé une corrélation non significative entre les mesures auto-rapportées et comportementales de la présence et une corrélation significative entre l'anxiété et les cybermalaises. De plus, l'anxiété n'a pas différé de manière significative entre les conditions expérimentales. Finalement, les cybermalaises et la stabilité posturale, ainsi que l'anxiété et la stabilité posturale, n'étaient pas significativement corrélés.

Bref, les résultats suggèrent que les mesures auto-rapportées et comportementales de la présence ne convergent pas nécessairement. Ils appuient également une relation entre l'anxiété et les cybermalaises. Cela pourrait avoir des retombées pour les applications qui induisent l'anxiété. La recherche future devrait envisager d'utiliser diverses mesures de la présence et des méthodes permettant de distinguer l'anxiété et les cybermalaises.

Abstract

Presence, the perceptual illusion of "being there" in the virtual environment, is an essential component of virtual reality (VR). According to Slater, presence has two components: the place illusion and the plausibility illusion. Self-report measures are commonly used to measure presence in VR, but they are often administered after immersions and do not assess user behaviour in VR. Therefore, there is a need to use behavioural measures to assess presence, particularly in anxiety-provoking virtual environments, which are used in several areas.

Previous studies have shown that anxiety and multisensory stimulation affect presence. However, few studies have examined the role of multisensory integration mechanisms on presence, particularly in an emotional context. The second chapter of the thesis explored this topic more extensively and proposed a conceptual model of presence. Two experimental studies then examined the relationship between presence, anxiety, and multisensory stimulation in an anxiety-inducing context. The main objective was to evaluate a behavioural measure of presence, while documenting the convergence between subjective and objective measures of presence. This measure, based on previous studies, involves participants physically rotating their shoulders to cross narrow doors in VR.

The first experimental study (n = 25) evaluated the methodology to validate the virtual environments and the behavioural measure of presence in an emotional context. Participants were exposed to three experimental conditions: (1) Control, (2) Risk of falling, and (3) Risk of falling + Fire. During the immersions, participants physically walked on a plank and crossed the narrow virtual doors. The two conditions with the risk of falling included a deep virtual pit. Before and after the immersions, participants completed several questionnaires. The results revealed a non-significant correlation between the self-reported and behavioural measures of

presence, as well as a non-significant difference in anxiety across the experimental conditions. However, unexpected results indicated that self-reported presence and cybersickness, as well as anxiety and cybersickness, were significantly correlated.

The second experimental study (*n* = 25), a continuation of the first study, made modifications to the study protocol and the virtual environment to increase presence and anxiety. Then, similar to the first study, the study evaluated the behavioural measure of presence in a context of anxiety. Following the unexpected results from the first study regarding cybersickness, the study also explored the relationship between presence, anxiety, cybersickness, and postural stability using the behavioural measure, questionnaires, and force plates. Participants were exposed to two experimental conditions, rather than three: (1) Control and (2) Risk of falling. The results were similar to the first study and revealed a non-significant correlation between the self-report and behavioural measures of presence and a significant correlation between anxiety and cybersickness. Furthermore, anxiety did not significantly differ across experimental conditions. Finally, cybersickness and postural stability, as well as anxiety and postural stability, were not significantly correlated.

In summary, the results suggest that self-report and behavioural measures of presence may not necessarily converge. They also support a relationship between anxiety and cybersickness. This could have implications for anxiety-inducing applications. Future research should consider using a variety of measures to assess presence and methods that allow to distinguish between anxiety and cybersickness.

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Remerciements

Je tiens à remercier mon directeur de thèse, Stéphane Bouchard, ainsi que les membres de mon comité pour leur appui et leurs conseils techniques tout au long de ma thèse. J'aimerais également remercier David Labbé pour son soutien dans l'analyse des données et la révision de l'article de ma première étude expérimentale. Un grand merci à Marie-Christine, Paul, Maxence, Mathilde et Simon pour avoir développé les environnements virtuels utilisés dans mon projet de thèse. Sans eux, les études expérimentales n'auraient pas été possibles. Merci également à Meghan et Anne pour leur aide lors de la collecte de données. J'aimerais aussi remercier Giulia pour son soutien moral et ses précieux conseils. Enfin, merci à tous les participants d'avoir pris part aux études.

Je suis profondément reconnaissante envers ma famille et mes amies pour leur présence et leurs encouragements tout au long de ces presque dix dernières années. I would also like to extend my heartfelt thanks to my husband, Zak, who helped me through difficult times, supported me every step of the way, and encouraged me to complete my Ph.D. even when I felt like giving up.

Chapitre 1 : Introduction générale

La réalité virtuelle

La réalité virtuelle (RV), un champ d'étude prometteur et en pleine expansion, est utilisée dans divers domaines, notamment en psychothérapie (p. ex., pour traiter les troubles anxieux ; Wiederhold & Bouchard, 2014), en éducation (p. ex., pour former des pilotes, des militaires ; Romano & Brna, 2001), en divertissement (p. ex., pour développer des jeux vidéo ; Bowman & McMahan, 2007) et en médecine (p. ex., pour former des chirurgiens ; IJsselsteijn et al., 2000). La RV permet de simuler et d'étudier des situations dangereuses ou risquées dans l'environnement physique de manière contrôlée et sécuritaire. La recherche en RV aide, entre autres, à concevoir des environnements virtuels plus adaptés aux besoins des utilisateurs, par exemple, en personnalisant les environnements à visées psychothérapeutiques.

La RV peut être définie comme étant un ensemble de technologies informatiques offrant un environnement immersif, permettant à l'utilisateur de se sentir présent et d'interagir avec cette autre réalité en temps réel (Wiederhold & Bouchard, 2014). La RV peut désigner différentes technologies, telles que la vidéo immersive à 360° et les simulations immersives en 3D (Trahan et al., 2019). Dans la thèse, seulement ces dernières sont abordées, car les autres technologies ne sont pas pertinentes dans le contexte du projet (c.-à-d., les participants ont seulement été immergés dans des environnements synthétiques entièrement générés par ordinateur).

La recherche suggère que la RV berne en quelque sorte le cerveau en faisant croire que la stimulation sensorielle reçue via l'équipement de VR est crédible et se produit réellement, menant ainsi à des expériences illusoires (Gonzalez-Franco & Lanier, 2017). Si les stimuli de l'environnement virtuel engagent les sens de l'utilisateur de manière appropriée, ils sont traités comme s'ils provenaient de l'environnement physique (Bailenson, 2018). En d'autres mots, l'utilisateur réagirait aux stimuli dans l'environnement virtuel comme il le ferait dans l'environnement physique, même s'il sait consciemment que les stimuli sont virtuels (Trahan et al., 2019). Par exemple, un utilisateur immergé en RV va probablement se déplacer pour éviter un objet virtuel lancé dans sa direction, même s'il sait consciemment qu'aucun objet physique n'a été lancé.

Le système perceptuel ne dépend pas entièrement que de l'information reçue par les sens : il comble les lacunes perceptives et construit sa « réalité » en combinant l'information sensorielle qu'il reçoit avec les processus cognitifs descendants (*top-down*, de Gelder et al., 2018). Par exemple, un utilisateur pourrait ressentir des sensations tactiles même si l'environnement virtuel contient seulement des stimuli visuels. Lecuyer et al. (2000) ont révélé que les participants immergés en RV avaient l'impression de ressentir de la résistance tactile lorsqu'ils manipulaient des objets avec leurs mains virtuelles, même s'ils ne tenaient pas d'objets dans l'environnement physique. Parallèlement, Biocca et al. (2001) ont trouvé que les participants avaient ressenti de la résistance tactile lorsqu'ils « déplaçaient » des organes d'un cadavre virtuel ou des objets d'une caisse virtuelle, même si encore une fois seulement des stimuli visuels leur avaient été présentés.

Globalement, la recherche suggère que le processus d'intégration des stimuli provenant d'un environnement virtuel et de l'environnement physique est semblable. Par exemple, tout comme dans l'environnement physique, un délai important entre les stimuli visuels et vestibulaires peut mener à des malaises qui ressemblent au mal des transports. En effet, les cybermalaises peuvent se produire lorsqu'il y a un grand délai entre les mouvements de la tête et la mise à jour de la scène visuelle ou lorsque les mouvements de la tête sont larges ou rapides

(Allison et al., 2001). Bref, l'intégration multisensorielle joue un rôle important en RV (voir Berthiaume et al., 2018 et le Chapitre 2 pour une discussion plus détaillée).

L'immersion

Deux composantes fondamentales de la RV sont l'immersion et la présence. L'immersion désigne les caractéristiques objectives des technologies et peut être mesurée (Bowman & McMahan, 2007 ; Slater, 1999). Par exemple, la résolution d'écran de différentes technologies peut être mesurée et comparée. Selon Slater et Wilbur (1997), l'immersion réfère à la mesure dans laquelle la technologie utilisée pour immerger un individu en RV est (1) inclusive, (2) étendue, (3) enveloppante et (4) riche en stimuli. « Inclusive » désigne le degré d'exclusion de l'environnement physique. Par exemple, une voûte à six faces est plus inclusive qu'un écran d'ordinateur, car l'utilisateur ne peut pas voir l'environnement physique. « Étendue » fait référence au nombre de sens affectés par la technologie. Par exemple, une voûte immersive présentant des stimuli visuels, auditifs et tactiles est plus étendue qu'un écran d'ordinateur présentant seulement des stimuli visuels. « Enveloppante » réfère à la mesure dans laquelle la technologie est panoramique plutôt qu'étroite. Par exemple, dans une voûte à six faces, l'utilisateur peut voir l'environnement virtuel sur toutes les faces ; l'environnement virtuel l'entoure. « Riche en stimuli » désigne la résolution et la fidélité de la technologie. Par exemple, une voûte ayant un réalisme visuel plus élevé, une meilleure résolution et une fréquence d'actualisation rapide est plus fidèle à l'environnement physique qu'un écran d'ordinateur ayant un réalisme visuel plus faible, une faible résolution et une fréquence d'actualisation lente. Bref, le degré d'immersion d'une voûte est souvent plus élevé qu'un écran d'ordinateur. Ainsi, plus la technologie utilisée est inclusive, étendue, enveloppante et riche en stimuli, plus l'immersion sera élevée.

Des facteurs contribuant à l'immersion comprennent : l'étendue du champ de vision, le nombre de sens que la technologie stimule, la qualité du rendu pour chaque sens stimulé, l'étendue du suivi des mouvements des utilisateurs, le réalisme visuel (jusqu'à un certain point), le taux de mise à jour des images, la latence de présentation des images, la concordance des stimuli visuels et proprioceptifs et une perspective à la première personne (Sanchez-Vives & Slater, 2005). La stéréoscopie, la résolution de l'écran et la taille de l'écran y contribuent également (Bowman & McMahan, 2007).

La présence

Cette section a pour but d'introduire la présence, d'aborder quelques définitions de la présence utilisées dans le domaine de la RV et de faire un survol des termes qui sont souvent confondus avec la présence.

L'immersion et la présence sont souvent confondues. Contrairement à l'immersion, la présence réfère à une expérience subjective. Par exemple, un individu peut ressentir des niveaux de présence différents d'une immersion à l'autre, même si l'environnement virtuel et la technologie restent identiques. De plus, les niveaux de présence peuvent varier entre individus dans les mêmes conditions (Bowman & McMahan, 2007).

Le terme « présence » dérive du terme « téléprésence » utilisé à l'égard des téléopérateurs, ou des ouvriers à distance. Ces derniers se sentaient comme s'ils étaient dans leur lieu de travail à distance plutôt que dans celui où ils se trouvaient physiquement (Minsky, 1980 ; Witmer & Singer, 1998). Dans le domaine de la RV, la présence est un sentiment subjectif que les utilisateurs ressentent lorsqu'ils sont immergés en RV, peu importe la technologie utilisée. Plus précisément, la présence peut être définie comme étant l'illusion perceptuelle « d'être là » dans l'environnement virtuel (Heeter, 1992). Lombard et Ditton (1997) ont défini la présence comme étant une illusion de non-médiation, c'est-à-dire une illusion où l'utilisateur se sent comme s'il est dans une autre réalité et agit en conséquence sans tenir compte du fait que cette illusion est créée par un support technologique. Slater et Usoh (1993) ont défini la présence comme étant la suspension de l'incrédulité (*suspension of disbelief*[1]) où les utilisateurs mettent de côté temporairement leur scepticisme afin d'accepter le monde virtuel. Ils expliquent que les utilisateurs savent consciemment qu'ils se trouvent dans l'environnement physique, mais leurs sens leur font croire qu'ils sont dans l'environnement virtuel.

Parfois, la présence dans un environnement virtuel peut être puissante au point qu'un individu ne tient plus compte du fait qu'il se trouve physiquement dans un autre endroit. Par exemple, dans une étude, 65% des participants (13/20) ont rapporté qu'ils n'étaient pas ou peu conscients qu'ils se trouvaient physiquement dans un laboratoire durant l'immersion en RV (Welch et al., 1996).

Selon Slater (2009, 2018) et Slater et al. (2010, 2022), la présence est plus qu'un sentiment subjectif ; le comportement est également important. Ils suggèrent que trois éléments sont nécessaires pour que la RV fonctionne : (1) l'illusion de place (*place illusion*), (2) l'illusion de plausibilité (*plausibility illusion*) et (3) l'immersion. L'illusion de place réfère à la présence décrite ci-dessus : la perception subjective d'être dans l'environnement virtuel plutôt que dans l'environnement physique. Slater et al. (2010) comparent cette illusion à la perception de la « rougeur » de la couleur rouge, qui est également subjective et varie d'un individu à l'autre. L'illusion de plausibilité fait référence au sentiment que les événements dans l'environnement virtuel se produisent réellement (et est lié au réalisme perçu, ou le sentiment que l'environnement virtuel est réaliste). Ces deux illusions influencent le comportement des

[1] Certains termes importants ont été traduits de l'anglais vers le français et apparaissent entre parenthèses en italiques dans la thèse.

utilisateurs : plus les utilisateurs ont l'impression que les événements dans l'environnement virtuel se produisent réellement et se sentent comme s'ils sont dans l'environnement virtuel, plus ils agiront de manière réaliste dans celui-ci. L'immersion réfère plutôt aux caractéristiques objectives de la technologie utilisée pour immerger l'individu (Slater, 2009).

Des études récentes ont examiné l'illusion de place et l'illusion de plausibilité séparément en RV (p. ex., Azevedo et al., 2014 ; Beacco et al., 2021 ; Bergström et al., 2017 ; Caldas et al., 2024 ; Denzer et al., 2022 ; Pouke et al., 2022 ; Rovira et al., 2009 ; Slater et al., 2013 ; Slater et al., 2023). Quelques études ont exploré des manipulations cognitives (p. ex., les attentes des participants) et perceptuelles (p. ex., la gravité des objets virtuels) qui peuvent briser les deux illusions (Brübach et al., 2022, 2023 ; Hofer et al., 2020 ; Skarbez et al., 2017, 2018, 2021 ; Skarbez et al., 2022 ; Westermeier et al., 2023). Une autre étude a examiné les biosignaux liés aux deux illusions en utilisant l'électroencéphalographie (Bahavan et al., 2023).

Des études ont également examiné l'illusion de plausibilité dans un contexte social, plus précisément en lien avec le développement d'humains virtuels, par exemple : leurs animations et leurs interactions avec l'utilisateur (Gruber & Kaplan-Rakowski, 2020), leur apparence visuelle (Wolf et al., 2022), les interactions possibles perçues selon la représentation corporelle (Dufresne et al., 2024), leur niveau de photoréalisme (Zibrek & McDonnell, 2019), leur congruence avec l'environnement et l'effet Proteus (Mal et al., 2023). D'autres études ont examiné la plausibilité et la cohérence des interactions des utilisateurs avec des humains virtuels ou des objets dans l'environnement virtuel (p. ex., Bengtsson & Couvering, 2022 ; Yu, 2019).

Quelques études ont exploré l'illusion de place et l'illusion de plausibilité dans un contexte émotif (p. ex., Brübach et al., 2025 ; Lin, 2017 ; Shin et al., 2024). Bien que les auteurs ne réfèrent pas à l'illusion de plausibilité de Slater directement, Makhsadov et al. (2022) ont intégré un téléphone intelligent physique dans différents scénarios en RV afin d'étudier la plausibilité. Toutefois, les résultats des études examinant l'illusion de plausibilité jusqu'à présent demeurent préliminaires (et parfois mitigés) et les variables influençant cette illusion méritent d'être explorées plus en profondeur.

Pour résumer, les utilisateurs immergés en RV ont l'impression que les événements dans l'environnement virtuel se produisent réellement (illusion de plausibilité) et ils y réagissent souvent implicitement en conséquence. Si les événements dans l'environnement virtuel paraissent comme s'ils se produisent réellement, les utilisateurs auront l'impression de se trouver dans l'environnement virtuel, même s'ils savent consciemment qu'ils sont physiquement dans un autre endroit (illusion de place), ce qui influence également leur comportement. Dans le même sens, les individus répondent souvent implicitement à une situation effrayante et réalisent consciemment par la suite qu'il n'y a aucun danger. Slater (2018) a expliqué que les utilisateurs auront une réaction physiologique très rapide aux stimuli virtuels et se rendront compte plus tard qu'ils ne font pas physiquement face aux stimuli. Le projet de thèse s'inspire de cette théorie.

Parallèlement, Weber et al. (2021) soutiennent que la présence a deux dimensions : (1) le sentiment « d'être là » dans l'environnement virtuel et (2) le réalisme perçu (ou le réalisme subjectif). Ils expliquent que lorsque les utilisateurs sont immergés dans un environnement virtuel, ils comparent les objets virtuels et les personnages virtuels à ceux se trouvant dans l'environnement physique et évaluent la cohérence et la crédibilité des objets, des personnages et du scénario. Ce jugement peut varier d'un utilisateur à un autre en fonction de leur expérience antérieure et de leurs caractéristiques individuelles (p. ex., leurs attentes envers l'environnement virtuel). Cette définition de la présence ressemble à celle mise de l'avant par Slater (2009, 2018) et Slater et al. (2010, 2022).

Plusieurs concepts peuvent être confondus avec la présence ; il est important de faire une distinction entre eux. La présence est fréquemment confondue avec les émotions, l'engagement, l'implication et l'attention de l'utilisateur (Slater, 2003 ; Slater, Lotto et al., 2009). Par exemple, un individu peut écouter de la musique en RV et se sentir présent dans l'environnement virtuel, mais ne pas s'intéresser à la musique (présence élevée, implication faible ; Slater et al., 2009). Un utilisateur pourrait également être engagé dans l'environnement virtuel (p. ex., il complète la tâche requise), mais il ne se sent pas présent (p. ex., il ne prend pas l'environnement virtuel au sérieux, il sait qu'il se trouve physiquement dans un laboratoire ; engagement élevé, présence faible). D'autre part, un individu pourrait se trouver dans un aéroport virtuel (ou un autre endroit) et se sentir présent dans l'environnement virtuel, mais ne pas ressentir d'émotion face aux événements qui se produisent ou aux gens qui se déplacent dans le bâtiment (présence élevée, émotion faible ; Slater 2003). Finalement, un utilisateur pourrait se sentir présent dans un environnement virtuel sans porter attention à tout ce qui se passe dans celui-ci (présence élevée, attention faible). Bref, il est important de faire une distinction entre les différents termes, car la multiplication des termes utilisés en recherche peut mener à la confusion, des désaccords et une difficulté à communiquer entre chercheurs et à combiner les résultats des différentes études (Lee, 2004 ; Slater, 2003).

Des chercheurs ont proposé différents types de présence, et ces sous-types peuvent également être confondants (p. ex., Biocca et al., 2003 ; Riva et al., 2004), car ils ne réfèrent pas nécessairement à la RV (p. ex., présence au cinéma). La thèse se limite à la présence en RV (provenant des supports technologiques pour les immersions en RV ; c.-à-d., l'expérience vécue en RV). Le terme « présence » seul est utilisé afin d'alléger le texte, sauf lorsqu'il s'avère important de distinguer les sous-types d'illusion de plausibilité ou de place. La présence au sens large (c.-à-d., vécue dans le quotidien, voir Nunez et al., 2007 pour une discussion plus détaillée) ne sera pas discutée (p. ex., les gens peuvent se sentir présents dans leur vie quotidienne, même s'ils ne sont pas immergés en RV). La discussion de la présence au sens large n'est pas nécessaire, car elle pourrait porter à confusion et le projet de thèse examine seulement la présence en RV.

Des facteurs influençant la présence

Dans cette section, quelques facteurs ayant un effet sur la présence sont présentés. Dans leur méta-analyse, Cummings et Bailenson (2016) ont trouvé que l'augmentation du suivi des mouvements des utilisateurs, l'utilisation de la stéréoscopie et l'élargissement du champ de vision avaient de plus grands effets sur la présence que l'amélioration du contenu visuel et auditif et la perspective de l'utilisateur dans l'environnement virtuel (perspective égocentrique ou exocentrique). D'autres facteurs pouvant influencer la présence comprennent le délai du feedback visuel, la résolution des images, le degré de similarité entre le corps virtuel et physique, la présentation des images en couleur versus en noir et blanc (Welch et al., 1996), l'animation des images, la taille de l'écran, la présentation stéréoscopique des images (Hendrix & Barfield, 1995 ; Hendrix & Barfield, 1996a ; IJsselsteijn et al., 2001), le suivi de la tête (*head tracking*, Hendrix & Barfield, 1995 ; Hendrix & Barfield, 1996a), les délais du casque de RV (Kim, Moroz, et al., 2018 ; Kim, Luu, & Palmisano, 2020), la latence de présentation des images (Meehan et al., 2003 ; Meehan et al., 2005) et le champ de vision (Lin et al., 2002 ; Prothero & Hoffman, 1995 ; Stanney & Salvendy, 1998).

Parmi les facteurs pouvant avoir un impact sur la présence, le réalisme visuel est souvent discuté. Plusieurs études ont montré que le réalisme visuel influence la présence (Brade et al., 2021 ; Khanna et al., 2006 ; Hvass et al., 2017a, 2017b ; Mania, 2001 ; Mania & Robinson, 2004 ;

Newman et al., 2021 ; Slater, Khanna, et al., 2009 ; Slater, Usoh, & Chrysanthou, 1995 ; Yu et al., 2012). Toutefois, d'autres études ont révélé que le niveau de réalisme visuel n'a pas eu d'effet sur la présence (p. ex., Zimmons & Panter, 2003 ; Smith & Mulligan, 2021). Bien qu'améliorer le réalisme visuel puisse augmenter la présence, le développement d'environnements virtuels représentant précisément l'environnement physique (la géométrie, l'éclairage et les propriétés des matériaux) en temps réel est dispendieux et fastidieux en raison de l'expérience technique (p. ex., coûts de formation), du temps et du matériel (p. ex., licences, ordinateurs puissants) requis pour atteindre une telle précision (Gonçalves et al., 2022 ; Molina et al., 2020 ; Newman et al., 2022 ; van Gisbergen et al., 2019).

De plus, il n'est peut-être pas nécessaire de reproduire l'environnement physique avec exactitude, car la vision humaine peut être bernée (Chalmers & Ferko, 2008 ; de Gelder et al., 2018 ; Reinhard et al., 2013). L'information sensorielle reçue par le système visuel interagit avec les processus cognitifs descendants (*top-down*) pour créer une représentation mentale cohérente et donc même un environnement virtuel avec un réalisme visuel réduit peut induire la présence (IJsselsteijn, 2002). Par exemple, les utilisateurs immergés dans une forêt virtuelle avec un nombre de polygones réduit reconnaissent qu'il s'agit d'une forêt, même si elle ne ressemble pas exactement à une forêt physique (Mizuho et al., 2023). En d'autres mots, l'environnement virtuel n'a pas besoin d'être une copie exacte de l'environnement physique pour être efficace. En fonction de la tâche et du contexte, les propriétés des objets nécessaires (p. ex., leur forme géométrique, leur taille, leur position, leurs mouvements et leurs matériaux) pourraient rester plus fidèles à l'environnement physique (Ferwerda, 2003) alors que celles qui sont superflues pourraient être moins réalistes (Brade et al., 2021 ; Gonçalves et al., 2021 ; Ramic et al., 2007 ; Ramic-Brkic et al., 2013). Parallèlement, la présence pourrait être renforcée en ajoutant des stimuli auditifs, tactiles et olfactifs aux environnements virtuels, sans nécessairement ajouter de détail visuel (Dinh et al., 1999 ; Meehan et al., 2002 ; Munyan III et al., 2016).

Des facteurs liés à l'expérience antérieure de l'utilisateur et au scénario peuvent également avoir un impact sur la présence, tels que les attentes (Nunez, 2004), l'amorçage contextuel (Cerda et al., 2021 ; Nunez & Blake, 2003), la crédibilité de l'environnement virtuel ou du scénario (Bouvier, 2008) et le réalisme subjectif ou perçu (Bouchard, Dumoulin et al., 2012 ; Skeva et al. 2021). D'autre part, le scénario doit engager l'individu dans l'environnement virtuel pour induire une présence élevée (Slater & Wilbur, 1997).

La capacité d'interagir avec l'environnement virtuel est également importante : la présence augmente lorsque l'individu peut interagir avec l'environnement virtuel plutôt que seulement pouvoir l'observer (IJsselsteijn, 2002 ; Welch et al., 1996). Par exemple, on se sent généralement plus présent lorsque nous sommes immergés en RV avec une perspective égocentrique que lorsque nous sommes immergés avec une perspective exocentrique ou lorsque nous écoutons un film ou la télévision. Welch et al. (1996) ont montré que les utilisateurs se sentaient plus présents lorsqu'ils conduisaient un véhicule virtuel que lorsqu'ils étaient passagers dans le véhicule. Le réalisme d'un environnement virtuel avec lequel on ne peut pas interagir est réduit, car dans l'environnement physique, on peut interagir avec les objets et les individus qui nous entourent.

Le contexte de la tâche et les préférences perceptuelles de l'individu peuvent également avoir un effet sur la présence (Slater & Usoh, 1993a, 1993b ; Slater & Wilbur, 1997). Par exemple, lorsqu'un individu préférant les stimuli visuels est immergé dans un environnement virtuel où seulement des stimuli auditifs sont présentés, il ne se sentira pas aussi présent qu'un individu préférant les stimuli auditifs. D'autres facteurs individuels pouvant influencer la présence comprennent l’âge (Schuemie et al., 2005), le sexe (Bayro et al., 2022) et l’expérience antérieure avec les jeux vidéo (Romano & Brna, 2001). Toutefois, certaines études ont montré une corrélation négative ou non significative entre la présence et l’âge (Schaik et al., 2004), le sexe (Lorenz et al., 2023) et l’expérience antérieure avec les jeux vidéo (Usoh et al., 1999).

Plusieurs chercheurs ont divisé les facteurs ayant un impact sur la présence en facteurs humains (p. ex., caractéristiques de l’utilisateur/différences individuelles, Lindeman & Beckhaus, 2009 ; Ling et al., 2013 ; Lombard & Ditton, 1997 ; Wallach et al., 2010) et technologiques ou immersifs (p. ex., caractéristiques des supports technologiques/de la technologie utilisée, Lombard & Ditton, 1997). Par exemple, Sas et O’Hare (2003) ont proposé que des facteurs cognitifs (l’imagination créative, l’absorption et l’empathie) et les traits de personnalité (extraversion-introversion, sensation-intuition, pensée-sentiment et jugement-perception) influencent la présence. Récemment, Michaux et al. (2025) ont révélé une corrélation positive entre certains traits de personnalité et la présence, ainsi qu’entre le besoin de contrôle et la présence. Slater et Usoh (1993a) et Slater et al. (1994) ont suggéré que les facteurs internes (subjectifs) et externes (environnementaux, technologiques) ont un effet sur la présence. Witmer et Singer (1998) ont proposé que l’implication et l’immersion aient un impact important sur la présence. Finalement, IJsselsteijn et al. (2000) ont suggéré que l’étendue et la fidélité de l’information sensorielle, la concordance des actions de l’utilisateur et ce qu’il perçoit, les facteurs de contenu et les caractéristiques de l’utilisateur affectent la présence.

Bref, la recherche suggère que de nombreux facteurs ont un effet sur la présence. Cependant, les facteurs ayant l’effet le plus important sur celle-ci et la manière la plus appropriée de la mesurer méritent d’être explorés plus en profondeur. Quelques facteurs discutés dans les prochaines sections comprennent : les émotions (l’anxiété) et la stimulation multisensorielle.

Les émotions. Dans cette section, l'impact des émotions sur la présence est discuté. En premier, des environnements virtuels induisant des émotions sont présentés. Ensuite, des études ayant examiné l'anxiété et la présence sont décrites. La thèse s'attarde à l'anxiété plutôt qu'aux autres émotions, car cette émotion est fréquemment provoquée en RV. Finalement, des études ayant examiné l'anxiété, la présence et des facteurs technologiques sont abordées. L'étude des émotions en RV aide à développer des environnements virtuels émotionnels efficaces (p. ex., des simulateurs pour la formation et des environnements virtuels à visées psychothérapeutiques pour traiter les troubles anxieux). Il est important de comprendre le rôle de la présence dans un contexte émotionnel, car on s'attend à ce que les utilisateurs réagissent de manière semblable en RV que dans l'environnement physique et vice versa.

Des études ont montré qu'il est possible d'induire diverses émotions en RV. Par exemple, Riva et al. (2007) ont examiné l'effet des émotions sur la présence et si différents environnements virtuels pouvaient induire différentes émotions. Les résultats ont indiqué que les participants avaient ressenti de l'anxiété et de la tristesse, ainsi qu'une réduction du bonheur et de l'affect positif, lorsqu'ils naviguaient dans un parc virtuel anxiogène. Ils avaient ressenti une augmentation de calme et de bonheur, ainsi qu'une réduction de la tristesse, la colère, l'anxiété et l'affect négatif, lorsqu'ils naviguaient dans un parc virtuel relaxant. Il n'y avait pas de changements dans leurs émotions lorsqu'ils naviguaient dans un parc virtuel neutre. De plus, les résultats ont montré que la présence était significativement plus élevée lorsque les participants naviguaient dans le parc anxiogène et le parc relaxant que dans le parc neutre. Finalement, l'ampleur de la présence prédisait l'anxiété que les participants ressentaient dans le parc anxiogène (un participant ayant une présence élevée ressentait un niveau d'anxiété plus élevé).

Des études plus récentes ont également trouvé que différents environnements virtuels suscitaient différentes émotions et avaient un effet sur la présence (p. ex., Felnhofer et al., 2015 ; Jicol et al., 2021 ; Oliveira et al., 2018 ; Voigt-Antons et al., 2021 ; Wang et al., 2022). Une de ces études (Oliveira et al., 2018) a révélé que la présence des participants était plus élevée lorsqu'ils étaient exposés à un environnement virtuel induisant de l'éveil par rapport à un environnement virtuel relaxant ou abstrait. Ce résultat suggère que la présence est plus élevée dans les environnements virtuels induisant des émotions plus intenses.

La présence semble également jouer un rôle dans d'autres scénarios en RV impliquant une composante émotionnelle. Par exemple, une étude (Simon et al., 2020) a examiné la relation entre la présence et l'envie de consommer de l'alcool (*alcohol craving*) post-immersion chez des participants consommant de l'alcool occasionnellement (*occasional drinkers*) et des participants consommant de l'alcool de manière excessive (*heavy drinkers*). Les participants étaient immergés dans un bar virtuel pendant environ 5 minutes. Les résultats ont montré que la perception de la validité écologique de l'environnement virtuel (une dimension de la présence dans le questionnaire utilisé) avait un effet significatif sur l'envie de consommer de l'alcool post-immersion, particulièrement chez les participants consommant de l'alcool de manière excessive. Ces résultats suggèrent que la présence pourrait être une variable pertinente à considérer dans les études utilisant des environnements virtuels simulant des scénarios comportant une composante émotionnelle, tels que ceux liés aux dépendances.

D'autres études ont utilisé des environnements virtuels contenant des fosses profondes virtuelles pour induire l'anxiété (p. ex., Slater, Usoh, & Steed, 1995 ; Usoh et al., 1999 ; Meehan et al., 2002, 2003). Les résultats ont montré que l'activation physiologique et l'anxiété rapportée des participants ont augmenté lorsqu'ils étaient exposés à ces environnements virtuels anxiogènes. Martens et al. (2013) ont obtenu des résultats semblables lorsqu'ils ont exposé des participants à un scénario virtuel anxiogène dans un ascenseur : la conductivité de la peau, le pouls et le niveau d'anxiété rapportée des participants étaient plus élevés que ceux dans la condition contrôle. Plus récemment, des participants ont été immergés dans une salle virtuelle nommée « *Room 101* », un environnement virtuel anxiogène contenant du feu, des araignées, des explosions, un sol qui s'écroule, etc. L'exposition à cet environnement virtuel a augmenté l'activation physiologique et l'anxiété rapportée des participants (McCall et al., 2015 ; McCall et al., 2016). Bref, les environnements virtuels anxiogènes semblent induire efficacement l'anxiété.

Des études précédentes ont examiné la relation entre l'anxiété et la présence. Par exemple, Bouchard et al. (2008) ont étudié l'effet de l'anxiété sur la présence chez 31 participants ayant une phobie des serpents. Les participants ont été divisés aléatoirement en deux conditions : (1) exposition à un environnement virtuel anxiogène en premier ou (2) exposition à un environnement virtuel non anxiogène en premier. Tous les participants étaient exposés à un environnement virtuel neutre avant les deux autres conditions. La tâche des participants était d'explorer l'environnement virtuel (un désert). Dans l'environnement virtuel anxiogène, les participants étaient informés qu'il y avait des serpents venimeux, dangereux et agressifs cachés dans le sable et qu'ils ne les attaqueraient pas, mais ils devraient être sur leurs gardes (l'environnement virtuel ne contenait pas réellement de serpents). Dans l'environnement virtuel non anxiogène, les participants exploraient le même environnement, mais ils étaient informés qu'il n'y avait pas de serpents (l'environnement virtuel n'en contenait pas non plus). Les résultats d'une mesure verbale ont montré que la présence des participants était plus élevée lorsqu'ils étaient exposés à l'environnement virtuel anxiogène que l'environnement virtuel neutre ou non anxiogène. D'autre part, la présence était plus élevée chez les participants exposés à l'environnement virtuel non anxiogène en premier que chez ceux exposés à l'environnement virtuel anxiogène en premier. Selon les résultats de la mesure verbale, l'anxiété semblait donc mener à une présence plus élevée (et possiblement vice versa). Cependant, les résultats des questionnaires ont indiqué le contraire : la présence a diminué lorsque les participants étaient exposés à l'environnement virtuel anxiogène. En d'autres mots, la présence a diminué lorsque l'anxiété a augmenté.

De nombreuses autres études ont trouvé une relation entre l'anxiété et la présence, où plus l'émotion est forte, plus la présence est élevée (p. ex., Alsina-Jurnet et al., 2011 ; Gromer et al., 2019 ; Kisker et al., 2021 ; Renaud et al., 2002 ; Robillard et al., 2003 ; Schuemie et al., 2001 ; Shah & Lawson, 2025). Toutefois, la direction de la relation causale demeure toujours incertaine. En d'autres mots, l'anxiété pourrait augmenter la présence, mais la présence pourrait également augmenter l'anxiété. Par exemple, Steinhaeusser et al. (2023) ont trouvé que la présence induite par la technologie utilisée (PC versus RV versus RV + stimuli multisensoriels) semblait avoir un effet de médiation sur le niveau de peur et d'anxiété des participants. Dans deux études, Maymon et al. (2024) ont montré une relation significative entre la présence et la peur lorsque les participants se déplaçaient sur une planche virtuelle en hauteur. Cependant, les résultats ont révélé une relation non significative entre la présence auto-rapportée et les mesures physiologiques (rythme cardiaque et conductivité électrique de la peau). La forme de la relation entre la présence et l'anxiété est également incertaine, quoique Bouchard, Robillard, et al. (2012) ait suggéré qu'elle est possiblement non linéaire.

Il est important de noter que des études ont révélé une corrélation négative entre la présence et l'anxiété (p. ex., Ling et al., 2012 ; Villani et al., 2012). Une étude récente (Morel et al., 2025) a montré une corrélation négative entre l'anxiété et une dimension de la présence

(Engagement). Toutefois, les autres dimensions de la présence n'étaient pas corrélées à l'anxiété (Présence spatiale, Caractère naturel/Validité écologique et Effets négatifs). De plus, les résultats ont indiqué des différences individuelles entre les participants. En d'autres termes, la relation entre la présence et l'anxiété demeure complexe. L'étude de la relation entre l'anxiété et la présence permettrait de mieux personnaliser les environnements virtuels et d'améliorer leur efficacité (p. ex., si une présence minimale est requise afin qu'un traitement en RV soit efficace, il n'est pas nécessaire d'investir dans des technologies dispendieuses telles qu'une voûte, Bouchard, Robillard, et al., 2012). Pour une recension des écrits détaillée sur la présence et l'anxiété, voir la méta-analyse de Ling et al. (2014).

Des facteurs technologiques peuvent également avoir un effet sur les émotions. Par exemple, Baños et al. (2004) ont montré que l'immersion (écran d'ordinateur versus projecteur versus casque de RV) avait un effet plus large sur la présence lorsque les participants naviguaient dans un parc virtuel neutre. Cependant, les émotions avaient un effet plus large sur la présence lorsque les participants naviguaient dans un parc virtuel triste. Dans une autre étude, Kim et al. (2014) ont montré qu'une immersion dans une voûte ou avec un casque de RV avait induit une réponse émotionnelle plus élevée qu'un écran d'ordinateur. De plus, l'immersion dans la voûte avait suscité une réponse émotionnelle plus élevée qu'avec le casque de RV et l'écran d'ordinateur. Juan et Pérez (2009) ont indiqué qu'une immersion dans une voûte avait provoqué des niveaux d'anxiété et de présence plus élevés que celle avec un casque de RV chez des participants exposés à une hauteur en RV. Baños et al. (2008) et Peperkorn et al. (2015) ont révélé que la stéréoscopie avait un effet sur la présence et les émotions. Gorini et al. (2011) ont trouvé que l'immersion et le contexte narratif avaient un impact sur l'anxiété et la présence.

Finalement, Kwon et al. (2013), Ling et al. (2012) et Phillips et al. (2010) ont montré que le réalisme visuel pouvait avoir un impact sur l'anxiété.

Toutefois, quoiqu'une immersion élevée puisse contribuer à une expérience plus positive chez les utilisateurs, ce n'est pas nécessairement le cas (p. ex., Oh et al., 2019). Botella et al. (1999) ont montré qu'il est possible d'utiliser de l'équipement de moins bonne qualité sans nuire à l'expérience des participants.

Bref, l'anxiété peut être induite efficacement en RV (p. ex., Maïano et al., 2011 ; Pallavicini et al., 2018) et avoir un impact sur la présence (p. ex., Huang & Alessi, 1999). De plus, il semble y avoir une relation entre la présence et l'anxiété, ce qui motive le projet de thèse. L'anxiété a été choisie plutôt que d'autres émotions, telles que la tristesse ou le bonheur, car elle est souvent induite dans les environnements virtuels.

Afin de contextualiser les informations abordées jusqu'à maintenant, on peut se permettre d'annoncer tout de suite une partie de la méthodologie des deux études expérimentales présentées dans la thèse. Ainsi, afin d'induire de l'anxiété dans les études, les participants étaient exposés à une fosse profonde virtuelle, car la peur des hauteurs est une peur commune (Abelson & Curtis, 1989 ; Andreassi, 1995 ; Poulton & Menzies, 2002). Spécifiquement, les participants se trouvaient au huitième étage d'un gratte-ciel virtuel en construction (hauteur virtuelle de 35 m à partir du rez-de-chaussée virtuel). Cette hauteur a été choisie en raison des résultats obtenus par Wuehr et al. (2019), qui ont constaté que l'anxiété des participants était saturée à des hauteurs supérieures à 40 m. De plus, des études ont montré que l'exposition à des hauteurs élevées en RV était efficace pour augmenter les niveaux d'anxiété auto-rapportés, physiologiques (Boccignone et al. 2023 ; Gromer et al., 2019 ; Kisker et al., 2021 ; Luong & Holz, 2022 ;

Peterson et al., 2018 ; Schöne et al., 2023 ; Shah et Lawson, 2025 ; Zhu et al., 2021) et comportementaux des participants (Phillips et al., 2010 ; Zhu et al., 2021).

En outre, la première étude expérimentale du projet s'est appuyée sur les résultats de McCall et al. (2015, 2016) et a également simulé un feu virtuel qui se déclenchait dans l'échafaud du gratte-ciel en construction. L'hypothèse était que cette deuxième manipulation devrait induire de l'anxiété chez tous les participants (surtout chez ceux ne craignant pas les hauteurs), car la peur du feu est innée.

La stimulation multisensorielle. Dans cette section, l'effet de la stimulation multisensorielle sur la présence est discuté. Puisque plusieurs sens ont été stimulés dans les études de la thèse (c.-à-d., la vision, l'ouïe, le toucher), il semble utile de documenter l'impact de la stimulation multisensorielle sur la présence et les émotions. En premier, des études ayant examiné la stimulation multisensorielle et la présence sont présentées. Ensuite, des études ayant examiné l'anxiété, la présence et la stimulation multisensorielle sont abordées.

Les immersions en RV privilégient majoritairement la vision, l'ouïe et le toucher ; il existe peu de systèmes de RV impliquant les autres sens (l'olfaction et le goût). Un exemple d'un système stimulant plusieurs sens provient de l'Allemagne, où des chercheurs ont développé un environnement virtuel contenant des images, du son, de la chaleur, du vent et du retour haptique (Fröhlich & Wachsmuth, 2014). Pour ce faire, les chercheurs ont apporté des ajustements à une voûte en ajoutant des haut-parleurs, des ventilateurs, un dispositif de chauffage et des appareils qui suivent le mouvement des doigts des utilisateurs. Bien qu'il soit difficile de concevoir un tel système multisensoriel en raison des nombreuses contraintes à respecter (Gallace et al., 2012), la recherche sur le développement d'environnements virtuels impliquant d'autres sens est utile. Ces environnements virtuels représentent plus fidèlement l'environnement physique, affectent la présence et permettraient de réduire le coût lié à l'amélioration du réalisme visuel.

De nombreuses études ont montré que la présence des participants était plus élevée lorsque plusieurs sens étaient stimulés (p. ex., Baus & Bouchard, 2017 ; Baus et al., 2019 ; Baus et al., 2022 ; Chalmers et al., 2009 ; Cooper et al., 2015 ; Cui & Mousas, 2022 ; Gibbs et al., 2022 ; Gougeh & Falk, 2022 ; Gonçalves et al., 2025 ; Gougeh et al., 2022 ; Hendrix & Barfield, 1996b ; Hoffman et al., 1998 ; Marucci et al., 2021 ; Munyan III et al., 2016 ; Wagener et al., 2022 ; Yildirim et al., 2025). L'ajout de retour haptique peut également augmenter le réalisme de l'expérience en RV (p. ex., Apostolou et al., 2022 ; Turchet et al., 2012). Toutefois, une étude récente (Zholzhanova et al., 2025) n'a pas trouvé de différences significatives entre la présence des participants dans trois conditions : (1) condition avec des stimuli visuels et olfactifs, (2) condition avec des stimuli visuels seulement et (3) environnement physique.

La présentation de stimuli multisensoriels a également un effet sur les émotions (Freeman et al., 2004). Des études ont révélé qu'il est possible d'ajouter de la stimulation multisensorielle (p. ex., vibration d'une chaise, vent, odeur) à un environnement virtuel pour induire une certaine émotion, telle que le bonheur, la surprise ou l'anxiété (Kruijff et al., 2017). Peperkorn et Mühlberger (2013) ont rapporté que la présence était significativement plus élevée lorsque des stimuli visuels et tactiles étaient présentés en combinaison que lorsque des stimuli tactiles ou visuels étaient présentés seuls, suggérant que la présence était la plus élevée dans les conditions ressemblant le plus à l'environnement physique. Dans une autre étude, Shah et Lawson (2025) ont exposé 16 participants à un environnement virtuel où ils devaient marcher sur une planche en hauteur dans quatre conditions (ordre contrebalancé) : (1) stimuli audio-visuels seulement, (2) stimuli audio-visuels + planche physique instable, (3) stimuli audio-visuels + sensation de vent (provenant d'un ventilateur) et (4) stimuli combinés (audio-visuels + planche physique + vent). Les participants ont rapporté une présence et une anxiété plus élevées dans la condition avec les stimuli combinés. Le temps pour traverser la planche était également plus long dans les deux conditions avec la planche physique instable. Ces résultats suggèrent que la planche physique pourrait agir comme un signal spatial puissant, donnant l'impression aux participants « d'être là » dans l'environnement virtuel.

Dans une autre étude récente, Ribé-Viñes et al. (2025) ont examiné la relation entre la présence, l'anxiété et la stimulation multisensorielle. Spécifiquement, ils ont immergé 162 participants (population non clinique) dans une de deux conditions (ordre aléatoire) : (1) condition avec des stimuli visuels et auditifs seulement ou (2) condition avec des stimuli visuels, auditifs et tactiles. Pendant l'immersion, les participants marchaient sur une planche virtuelle en hauteur. Dans la condition avec des stimuli tactiles, il y avait une planche physique correspondante et une sensation de vent (provenant d'un ventilateur). La présence et l'anxiété étaient mesurées avant, pendant et après l'immersion via des questionnaires et des mesures verbales. Les résultats ont montré une corrélation positive significative entre la présence et l'anxiété pendant l'immersion. Toutefois, la corrélation entre les deux variables n'était pas significative après l'immersion. Ces résultats suggèrent que la relation entre la présence et l'anxiété est plus forte pendant l'exposition qu'après celle-ci. En outre, les résultats ont révélé une présence plus élevée dans la condition avec les stimuli multisensoriels. Cependant, il n'y avait pas de différences significatives entre les deux conditions en termes d'anxiété. Les auteurs ont proposé qu'un système de RV efficace pour l'exposition doive contenir des stimuli phobogènes appropriés et induire une présence suffisante (quoique pas nécessairement élevée) afin d'éliciter des réponses anxieuses. D'autre part, il se pourrait que chez les individus n'ayant pas de phobie, les stimuli tactiles améliorent la présence sans augmentation correspondante de l'anxiété, contrairement aux individus avec une phobie plus sévère.

Plusieurs études ont examiné l'effet de l'ajout de stimuli auditifs sur la présence et l'anxiété. Par exemple, Viaud-Delmon et al. (2006) ont comparé un environnement virtuel avec des stimuli visuels seulement et un deuxième avec des stimuli visuels et auditifs en combinaison chez deux groupes de participants (avec agoraphobie et sans agoraphobie). Les participants ont été exposés aux deux environnements virtuels dans un ordre de passation aléatoire. Leur tâche était de retrouver certains endroits dans une ville virtuelle et de se familiariser avec cette dernière. Les résultats ont indiqué que la présence était plus élevée lorsque les participants étaient exposés à la condition avec des stimuli visuels et auditifs en combinaison.

Dans une série d'études, Taffou et collègues ont examiné l'impact de stimuli visuels et auditifs sur la présence et l'anxiété en RV. Dans une première étude, Taffou et al. (2012) ont indiqué que des environnements virtuels avec des stimuli visuels et auditifs associés à un chien virtuel pouvaient induire de l'anxiété chez des participants avec une peur des chiens. Dans une deuxième étude, Taffou et al. (2013) ont comparé des participants avec et sans peur des chiens. Ils étaient exposés à un environnement virtuel avec des stimuli phobogènes visuels seuls, des stimuli auditifs seuls ou en combinaison. Les résultats ont révélé que les deux groupes de participants avaient ressenti une anxiété plus élevée lorsqu'ils étaient exposés aux stimuli visuels et auditifs en combinaison que seuls.

Finalement, dans leurs deux dernières études, Taffou et Viaud-Delmon (2014) et Taffou et al. (2017) ont montré qu'il y a une relation entre l'espace péripersonnel, l'anxiété et l'intégration multisensorielle. Plus précisément, lorsque des participants avec une peur des chiens étaient exposés à des stimuli phobogènes auditifs, leur espace péripersonnel (c.-à-d., l'espace entourant immédiatement leur corps, Rizzolatti et al., 1997) s'est élargi comparativement aux participants sans peur des chiens (Taffou et Viaud-Delmon, 2014). D'autre part, des participants avec une peur des foules ont ressenti un niveau d'anxiété plus élevée lorsque des stimuli visuels et auditifs phobogènes en combinaison étaient présentés plus près d'eux que lorsqu'ils étaient présentés plus loin (Taffou et al., 2017).

Diverses études (Hecht & Reiner Gad Halevy, 2006 ; Held & Durlach, 1992 ; Sheridan, 1992 ; Witmer & Singer, 1998) ont suggéré que la raison pour laquelle les individus se sentent plus présents dans un environnement virtuel où plusieurs sens sont stimulés est que cet environnement leur offre une expérience plus riche, complète et cohérente. De plus, ils ont proposé que plusieurs stimuli présentés ensemble soient traités plus rapidement qu'un stimulus présenté seul.

L'impact de l'intégration multisensorielle sur la présence en RV, particulièrement dans un contexte émotionnel, reste peu étudié. Un modèle conceptuel sur la présence propose que l'intégration multisensorielle soit nécessaire pour que la présence soit induite (voir Berthiaume et al., 2018 et le Chapitre 2 pour une discussion détaillée). Lorsque les stimuli virtuels sont temporellement congruents et cohérents (logiquement congruents/ont du sens), le cerveau évalue l'expérience dans l'environnement virtuel comme étant crédible et comme si elle se produisait réellement (illusion de plausibilité) (Gilbert, 2016 ; Skarbez, Brooks, et al., 2017 ; Skarbez, Neyret, et al., 2017 ; Skarbez et al., 2018 ; Skarbez et al., 2020 ; Slater, 2009), ce qui donne le sentiment d'être réellement dans l'environnement virtuel (illusion de place ; sentiment « d'être là » dans l'environnement virtuel).

Par exemple, si les utilisateurs ressentent peu de présence, ils pourraient passer à travers des objets virtuels lorsqu'ils se déplacent dans l'environnement virtuel, puisque la crédibilité de l'environnement virtuel est réduite. Toutefois, si un environnement virtuel représente une situation physique de manière réaliste, la présence pourrait être élevée, même si le réalisme visuel de l'environnement virtuel est réduit, car l'environnement virtuel reste crédible. Si un utilisateur voit une porte dans un environnement virtuel, il l'ouvrira probablement avant d'entrer dans l'autre pièce, même si la porte semble caricaturale. En d'autres termes, la crédibilité de l'environnement virtuel est importante pour que les utilisateurs aient l'impression que les événements se produisent réellement (illusion de plausibilité) et « d'être là » dans l'environnement virtuel (illusion de place).

Bref, la stimulation multisensorielle a un effet sur la présence et les émotions. Il est probable que plus le nombre de sens stimulés est grand, plus l'expérience dans l'environnement virtuel ressemble à celle dans l'environnement physique et donc plus l'impact sur la présence et les émotions est large. L'étude de la relation entre l'intégration multisensorielle et la présence permettrait de mieux comprendre les mécanismes impliqués pour induire la présence (voir Berthiaume et al., 2018 et le Chapitre 2 pour une discussion détaillée).

Mesures de la présence

La présence peut être mesurée de manière dichotomique ou continue. Si elle est mesurée de manière dichotomique, on dira que les utilisateurs ressentent de la présence ou n'en ressentent pas (Slater 2002 ; Slater & Steed, 2000). Selon cette position, ils ne pourraient pas ressentir « un peu » de présence, comme toute autre illusion perceptuelle simple. Ils ont le sentiment d'être dans l'environnement virtuel *ou* dans l'environnement physique. Quoiqu'il puisse être difficile pour les participants d'indiquer lorsqu'ils se sentent présents, il est généralement plus facile pour eux d'indiquer lorsqu'ils ne se sentent plus présents. Les interruptions de la présence (*breaks in presence*) réfèrent aux moments où ils réagissent aux stimuli dans l'environnement physique et la présence est interrompue (Slater et al., 2009). Par exemple, entendre un son fort dans le laboratoire ou entrer en collision avec les murs de la voûte pourrait briser la présence des participants. Il est possible de compter le nombre de fois que la présence a été brisée, ou le nombre de fois que le participant a fait la transition de l'environnement virtuel à l'environnement physique (Slater & Steed, 2000), ce qui peut être une mesure de la présence. Les interruptions de la présence sont considérées comme une mesure dichotomique de la présence : les participants se sentent présents ou non dans l'environnement virtuel (Nunez, 2007). Toutefois, l'expérience sur le terrain montre que les individus immergés en RV rapportent plus vivre la présence selon un continuum que de façon dichotomique.

Si la présence est mesurée de manière continue, les participants rapportent pouvoir se sentir, par exemple, pas du tout présents, très peu présents ou très présents. Les questionnaires de type Likert sont considérés comme des mesures continues de la présence (Nunez, 2007). La présence semble être continue, car les individus en immersion rapportent parfois avoir le sentiment d'être dans l'environnement virtuel et dans l'environnement physique simultanément. Par exemple, ils continuent de réagir aux stimuli dans l'environnement virtuel, mais mentionnent verbalement qu'ils savent qu'ils se trouvent dans un laboratoire. Cela suggère qu'ils peuvent ressentir une présence réduite.

Puisque la présence est difficile à définir et ses dimensions varient selon le cadre théorique, les chercheurs ne s'entendent pas sur la manière de la mesurer. Plusieurs mesures peuvent être utilisées pour l'évaluer, telles que les mesures auto-rapportées, physiologiques et comportementales, mais seules les principales sont discutées dans les prochaines sections.

Mesures auto-rapportées. Les mesures auto-rapportées (entre autres, les questionnaires, les mesures verbales et les entrevues ; Kelly, 2022) sont couramment utilisées et évaluent l'expérience subjective de se sentir « là » dans l'environnement virtuel (illusion de place) et le sentiment que les événements se produisent réellement (illusion de plausibilité). Il existe une foule d'outils de mesure auto-rapportés de la présence (voir Schuemie et al., 2001). L'*Independent Television Commission Sense of Presence Inventory* (ITC-SOPI) est illustré dans les prochains paragraphes.

L'ITC-SOPI a été développé par Lessiter et al. (2001). Il évalue la présence des participants après (Partie A du questionnaire) et durant (Partie B du questionnaire) l'immersion en RV. Il comprend quatre sous-échelles : (1) Présence spatiale (*Spatial Presence*), (2) Engagement (*Engagement*), (3) Caractère naturel/Validité écologique (*Naturalness/Ecological Validity*) et (4) Effets négatifs (*Negative Effects*). Le questionnaire a été utilisé dans les deux études expérimentales du projet de thèse. Il a été choisi, car il a été bien validé et a une bonne fidélité (alphas de Cronbach des sous-échelles allant de 0,76 à 0,94). De plus, il utilise une définition de la présence qui est également utilisée dans la thèse. Finalement, il n'y a pas actuellement de questionnaire validé pour évaluer l'illusion de plausibilité. La sous-échelle « Présence spatiale » a aidé à mesurer l'illusion de place et la sous-échelle « Caractère naturel/Validité écologique » a aidé à mesurer l'illusion de plausibilité.

Les mesures auto-rapportées sont utiles pour mesurer le sentiment subjectif de la présence. Toutefois, il est important de noter qu'elles ont des limites, dont, entre autres, les questionnaires complétés post-expérimentation évaluent la présence de manière rétrospective (IJsselsteijn et al., 2000). Les participants pourraient avoir oublié des détails de leur expérience, rendant les résultats moins fiables (Regal et al., 2019 ; Wiederhold et al., 2001). Pour pallier la limite de la mesure rétrospective, les participants peuvent remplir des questionnaires directement en RV pendant l'immersion (Gougeh & Falk, 2022 ; Regal et al., 2019 ; Schwind et al., 2019).

D’ailleurs, des chercheurs (Graf & Schwind, 2020) ont trouvé une incohérence entre la présence rapportée par les participants durant une immersion en RV et suivant l’immersion dans l’environnement physique. Une autre alternative est d’utiliser un dispositif avec un curseur que les participants tiennent dans leur main. Tout au long de l’immersion, ils peuvent déplacer le curseur sur le dispositif pour indiquer si la présence ressentie augmente ou diminue et les données sont enregistrées en temps réel sur un ordinateur (Freeman et al., 1999 ; IJsselsteijn et al., 2000). L’expérimentateur peut également demander aux participants leurs évaluations à l’oral (IJsselsteijn et al., 2000). Bouchard et al. (2004) ont développé une mesure verbale avec un item, qui demande aux participants d’évaluer la présence ressentie lorsqu’ils sont immergés en RV. Cependant, peu importe la façon de colliger l’information, la procédure d’auto-évaluation de la présence pendant l’immersion pourrait distraire les participants et réduire la présence ressentie.

Bien que ces méthodes permettent de mesurer la présence durant l’immersion, les participants doivent tout de même comprendre ce qu’est la présence et ce n’est pas nécessairement le cas. Les résultats provenant des mesures auto-rapportées peuvent alors être instables (Ellis, 1996 ; Freeman et al., 1999). En effet, les évaluations peuvent différer d’un participant à l’autre. En d’autres mots, les participants peuvent évaluer la présence différemment, car la compréhension du concept et l’expérience subjective vécue peuvent varier d’un participant à un autre. C’est souvent pour cela que les chercheurs vont effectuer une première immersion dans un environnement dit « contrôle » ou « neutre » afin que les participants se familiarisent avec la notion de présence.

Finalement, il n’y a toujours pas de consensus concernant la définition de la présence. En conséquence, il pourrait être difficile de déterminer si les mesures auto-rapportées sont les mesures les plus appropriées pour l’évaluer. Néanmoins, même si les mesures auto-rapportées ont leurs limites, elles sont tout de même importantes à utiliser, car elles informent sur l'expérience subjective des participants, contrairement aux autres mesures. Ainsi, il serait avantageux d'utiliser des questionnaires et des mesures supplémentaires (qui pallieraient les limites des questionnaires) pour avoir une perspective globale de la présence.

Mesures physiologiques. L'utilisation des mesures physiologiques se base sur l'argument que la présence et les émotions sont liées (Mestre, 2015) et donc, plus les utilisateurs se sentent présents, plus leur réaction physiologique devrait être forte. Des chercheurs suggèrent que les mesures physiologiques de la présence comprennent entre autres le rythme cardiaque, la conductivité électrique de la peau, la résistance de la peau, le taux de respiration, la pupillométrie et l'imagerie cérébrale (Athif et al., 2020 ; Insko, 2003 ; Meehan et al., 2005 ; Shah et al., 2025 ; Wiederhold et al., 2001). Les réactions physiologiques sont automatiques et implicites, donc elles sont considérées comme étant plus fiables (IJsselsteijn et al., 2000) et objectives que les mesures auto-rapportées. Contrairement à ces dernières, les participants n'ont pas besoin d'avoir une même interprétation de la présence.

Cependant, les mesures physiologiques semblent mesurer la réaction émotionnelle et l'activation physiologique plutôt que la présence en soi (Diemer et al., 2015). Par exemple, on s'attend à ce que le rythme cardiaque des participants augmente dans un environnement virtuel anxiogène (Bouchard et al., 2008), mais cette augmentation du rythme cardiaque mesure probablement l'activation physiologique plutôt que la présence (c.-à-d., la présence pourrait être faible même si le rythme cardiaque est élevé). Dans le même sens, lorsqu'on immerge des participants dans un environnement virtuel contrôle ou relaxant, on s'attend à ce que leur rythme cardiaque reste faible, car ils sont calmes. Si les participants ressentent une présence élevée, la direction de la relation entre le rythme cardiaque et la présence sera inversée. En d'autres termes, le rythme cardiaque ne correspond pas nécessairement au niveau de présence. Bref, les mesures physiologiques évaluent indirectement la présence et mesurent surtout la réaction aux stimuli. Bien que des mesures physiologiques aient été corrélées avec des mesures auto-rapportées de la présence, il faut faire attention de ne pas confondre les émotions et la présence.

Mesures comportementales. Les mesures comportementales évaluent la composante comportementale de la présence. Il existe diverses mesures comportementales utilisées en recherche sur la RV. Par exemple, des chercheurs ont proposé que les réflexes et le contrôle sensorimoteur soient des mesures comportementales acceptables alors que la performance ne l'est pas, car l'immersion plutôt que la présence pourrait contribuer à la performance (Mestre, 2015 ; Mestre & Fuchs, 2006). D'autres chercheurs ont proposé que les mouvements de la tête dans l'environnement virtuel corrèlent avec la présence (Holzwarth et al., 2021).

Essentiellement, le comportement des participants lors de la tâche est évalué : s'ils se sentent présents dans l'environnement virtuel, ils réagiront de manière semblable ou identique que dans l'environnement physique (Mestre, 2015). Par exemple, Spanlang et al. (2007) ont exposé des participants à un bar virtuel en feu. Ils ont trouvé que certains des comportements des participants ressemblaient à ceux qu'ils auraient dans l'environnement physique (p. ex., une participante a essayé d'éteindre le feu, une autre participante a essayé de reculer afin de s'éloigner du feu). Les mesures physiologiques semblaient également montrer que les participants ressentaient de l'anxiété. Cependant, aucun des participants n'a essayé de physiquement fuir le feu, ce qu'ils feraient si l'environnement physique était en feu. Il serait intéressant de mener d'autres études pour comparer le comportement des participants dans un environnement virtuel versus dans l'environnement physique.

Un autre exemple est le paradigme de la « passabilité » de différentes ouvertures (*passability of apertures*) développé par Warren et Whang (1987), qui sert à évaluer la perception des possibilités d'action (*perception of affordances*) dans l'environnement. Ce paradigme est inspiré de la théorie des possibilités d'action (*theory of affordances*) de Gibson (1979), qui soutient que la relation entre les propriétés d'un objet et les capacités d'un utilisateur déterminent les actions pouvant être effectuées avec l'objet. Plusieurs études dans l'environnement physique et en RV ont utilisé le paradigme de « passabilité » des portes où les participants doivent soit juger s'ils peuvent passer dans différentes largeurs d'ouverture de portes sans pivoter leur corps ou doivent traverser les portes (p. ex., Bhargava et al., 2020 ; Coelho et al., 2014 ; Fath et al., 2011 ; Geuss et al., 2010 ; Hackney et al., 2013 ; Higuchi et al., 2012 ; Wilmut & Barnett, 2010).

Dans deux études, Lepecq et al. (2009) et Mestre et al. (2016) ont utilisé des portes coulissantes virtuelles pour évaluer la présence en RV, qui implique que les participants pivotent physiquement leurs épaules pour passer dans des portes virtuelles exigües. La présence se quantifie par l'amplitude avec laquelle ils pivotent leurs épaules (p. ex., plus l'ouverture est étroite, plus ils devraient pivoter leurs épaules). Ainsi, s'ils se sentent présents, ils pivoteront leurs épaules afin de traverser les portes virtuelles (même si dans l'environnement physique, il n'y a pas de portes physiques devant eux), alors que ceux qui ne se sentent pas présents essayeront de les traverser sans pivoter leurs épaules et entreront en collision avec elles.

Lepecq et al. (2009) ont trouvé que le ratio critique moyen (c.-à-d., le ratio de la largeur de l'ouverture où chacun des participants pivotaient ses épaules sur la largeur de ses épaules) était de 1,22 pour les participants avec des épaules étroites et de 1,29 pour les participants avec des épaules larges. Deux participants n'ont pas pivoté les épaules pour traverser les portes virtuelles, peu importe la largeur de l'ouverture, donc leurs données ont été exclues des analyses. Il est intéressant de noter qu'il s'agit d'un comportement plus complexe qu'un réflexe, comme éviter un objet lancé au visage de la personne en immersion. Les participants pivotent leurs épaules seulement s'ils intègrent les stimuli virtuels comme étant crédibles et pertinents, alors qu'un réflexe pourrait être une réponse automatique et involontaire à un stimulus. Les résultats de l'étude de Lepecq et al. (2009) ont été reproduits par Mestre et al. (2016), qui ont trouvé un ratio critique moyen d'environ 1,4. Mestre et al. (2016) ont également intégré une représentation visuelle du corps et du retour haptique (dans deux des quatre conditions) dans leur environnement virtuel. Des études dans l'environnement physique où les participants devaient traverser des ouvertures étroites (*narrow aperture crossing*) ont rapporté des ratios critiques semblables (p. ex., Hackney et al., 2013 ; Higuchi et al., 2012 ; Wilmut & Barnett, 2010).

Une variable qui pourrait affecter la traversée des ouvertures (*aperture crossing*) est une menace posturale (*postural threat*). Par exemple, dans une étude (Hackney et al., 2015), 29 participants ont traversé une ouverture étroite à plusieurs reprises, soit au niveau du sol ou en hauteur (à 40 cm du sol) dans l'environnement physique. Les auteurs ont examiné plusieurs variables comportementales (p. ex., amplitude de rotation des épaules, vitesse de marche, stabilité posturale). Les résultats ont révélé que l'amplitude de rotation des épaules était plus petite dans la condition en hauteur que la condition au sol. De plus, les participants ont marché plus lentement en approchant l'ouverture et l'oscillation du tronc (*trunk sway*) était plus grande que la condition au sol. Ces résultats suggèrent qu'une menace posturale, telle que les hauteurs, peut avoir un impact sur le comportement des participants lorsqu'ils traversent des ouvertures étroites. Il serait utile de mener une étude semblable en RV, car celle-ci peut être utilisée pour simuler des scénarios dans des espaces étroits en hauteur (p. ex., sur un chantier de construction virtuel, Habibnezhad et al., 2019). Il serait également bénéfique d'explorer la relation entre les mesures auto-rapportées (p. ex., pour évaluer l'anxiété) et le comportement.

Une deuxième variable qui pourrait influencer l'amplitude de rotation des épaules est la distorsion de l'image corporelle. En général, les individus ressentant une insatisfaction corporelle croient et estiment que leur corps est plus large qu'il ne l'est réellement et sont insatisfaits de l'apparence de leur corps (la taille et la forme de leur corps et leur poids ; Gaudio et al., 2014). Ces individus pourraient exagérer l'amplitude de leurs rotations d'épaules, car ils perçoivent leur corps comme étant plus large qu'il ne l'est réellement. L'insatisfaction par rapport à son image corporelle est donc une variable qui a été mesurée dans le projet de thèse.

Dans l'état actuel des connaissances, il semble préférable d'utiliser différentes mesures de la présence afin d'obtenir une perspective plus globale de celle-ci. Par exemple, certains chercheurs suggèrent que la présence est un continuum, de réponses physiologiques et comportementales automatiques à un sentiment subjectif (Garau et al., 2008 ; Sanchez-Vives & Slater, 2005). La mesure comportementale des portes coulissantes virtuelles utilisée par Lepecq et al. (2009) et Mestre et al. (2016) est privilégiée dans la thèse. Cette mesure a été choisie, car plusieurs études antérieures ont montré qu'elle élicite un comportement naturel chez les participants (rotation des épaules) dans l'environnement physique et en RV. D'autre part, les menaces posturales, telles que les hauteurs, peuvent avoir un effet sur le comportement.

Synthèse

En résumé, la présence, une composante centrale de la RV, réfère à l'illusion perceptuelle « d'être là » dans l'environnement virtuel. Slater divise la présence en deux composantes : l'illusion de place (*place illusion*) et l'illusion de plausibilité (*plausibility illusion*), qui ont toutes les deux un impact sur le comportement des utilisateurs en RV. La présence est souvent mesurée à l’aide de mesures auto-rapportées. Cependant, ces dernières ont des limites. Les mesures comportementales permettent d’évaluer la présence en temps réel. L’utilisation de mesures comportementales serait utile dans des environnements virtuels anxiogènes qui visent à induire un comportement naturel (p. ex., psychothérapie, simulateurs). Ces mesures permettraient notamment d’examiner si les utilisateurs réagissent de manière semblable dans l’environnement virtuel que dans l’environnement physique.

Il existe peu de recherche examinant la relation entre la présence, l’anxiété et la stimulation multisensorielle en contexte d’anxiété, surtout en utilisant une combinaison de mesures auto-rapportées et comportementales. L’étude de ces facteurs pourrait aider à développer des environnements virtuels émotionnels plus efficaces. Les prochains chapitres présentent un modèle conceptuel de la présence, suivi d’un court chapitre sur les cybermalaises, puis deux études expérimentales menées dans le cadre de la thèse.

Chapitre 2 : A Novel Integrated Information Processing Model of Presence

(Article 1)

This chapter is a reprint of an article originally published as: Berthiaume, M., Corno, G., Nolet, K., & Bouchard, S. (2018). A novel integrated information processing model of presence. *Presence: Teleoperators and Virtual Environments*, *27*(4), 378-399. https://doi.org/10.1162/pres_a_00336. Reprinted with permission from MIT Press.

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A Novel Integrated Information Processing Model of Presence

Abstract

The objective of this article is to conduct a narrative literature review on multisensory integration and propose a novel information processing model of presence in virtual reality (VR). The first half of the article introduces basic multisensory integration (implicit information processing) and the integration of coherent stimuli (explicit information processing) in the physical environment, offering an explanation for people's reactions during VR immersions and is an important component of our model. To help clarify these concepts, examples are provided. The second half of the article addresses multisensory integration in VR. Three models in the literature examine the role that multisensory integration plays in inducing various perceptual illusions and the relationship between embodiment and presence in VR. However, they do not relate specifically to presence and multisensory integration. We propose a novel model of presence using elements of these models and suggest that implicit and explicit information processing lead to presence. We refer to presence as a perceptual illusion that includes a plausibility illusion (the feeling that the scenario in the virtual environment is actually occurring) and a place illusion (the feeling of being in the place depicted in the virtual environment), based on efficient and congruent multisensory integration.

1 Multisensory Integration in the Physical Environment

Prior to the 2000s, research on multisensory integration focused on the processing of information by each sense independently (Alais, Newell, & Mamassian, 2010). This first research perspective on multisensory integration posited that each sense processes information independently, which is then integrated in other areas of the brain (Treisman & Gelade, 1980). However, studies have suggested that there are multisensory neurons in the brain that are specifically used to integrate multisensory stimuli (e.g., in the superior colliculus) (King & Palmer, 1985; Meredith & Stein, 1983, 1985, 1986a, 1986b, 1987).

1.1 Input (Sensory Information)

Input is first received by the senses (i.e., vision, hearing, taste, olfaction, touch, proprioception) and needs to be processed and integrated. Multisensory

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Presence, *Vol. 27, No. 4, Fall 2018*, 378–399
https://doi.org/10.1162/PRES_a_00336

integration can be defined as the process by which inputs from two or more senses are combined to create a coherent representation of the world (Chalmers, Howard, & Moir, 2009; Stein, Stanford, & Rowland, 2009, 2014; Welch & Warren, 1980), which can affect perception, decisions, and overt behavior (Stein et al., 2009).

1.2 Implicit Information Processing

1.2.1 Multisensory Integration (Contingencies Match). Once the input is received by the senses, it is integrated in the corresponding sensory areas of the brain through implicit information processing (i.e., core information processes occurring very rapidly and without awareness). Certain conditions are necessary for stimuli to be integrated in a multisensory manner. This section focuses on two of three general multisensory integration principles (conditions): (1) the temporal principle (Alais et al., 2010; Klasen, Chen, & Mathiak, 2012; Spence & Squire, 2003), and (2) the spatial principle (Alais et al., 2010; King & Palmer, 1985; Klasen et al., 2012, Meredith & Stein, 1986a). The third principle is referred to as the principle of inverse effectiveness, but it is not discussed since it is not included in our model and is thus beyond the scope of this article (see Meredith & Stein, 1983, 1986b; Stein & Meredith, 1993 for a detailed discussion). These principles emerged from previous studies that examined multisensory neurons in cats, monkeys, and rodents (King & Palmer, 1985; Meredith, Nemitz, & Stein, 1987; Stein & Meredith, 1990, 1993). A deeper discussion of the temporal and the spatial principles is necessary given that our model is inspired from them.

1.2.1.1 Temporal Principle. Previous research has suggested that stimuli need to be presented close together in time (temporal principle) to be integrated in a multisensory manner (Alais et al., 2010; Klasen et al., 2012; Spence & Squire, 2003) and for a coherent representation of the environment to be created (Stein & Meredith, 1990). This allows individuals to respond faster and more appropriately to the environment (Stein & Meredith, 1990). When two stimuli are presented close together in time, individuals will perceive them as one event. When there is a significant delay between them, individuals will perceive them as two separate events (Keetels & Vroomen, 2012). Much of the research conducted in humans has focused on temporal windows and the perception of synchronicity. Although studies have shown that stimuli must be presented within a small temporal window to be perceived as one event (or synchronous), the exact size of the temporal window is unclear. Levitin, MacLean, Mathews, Chu, and Jensen (2000) examined the temporal window needed for participants to consider visual and auditory stimuli and tactile and auditory stimuli as synchronous. Specifically, the authors found that participants perceived the presentation of the stimuli as asynchronous when the auditory stimuli were presented 41 milliseconds (ms) before and 45 ms after the visual stimuli. Participants also perceived a delay when the auditory stimuli were presented 25 ms before and 42 ms after the haptic stimuli. While these results are preliminary because they are based on a small sample ($N = 8$), they suggest that the temporal window should be very small for stimuli to be perceived as synchronous.

There appears to be a tolerance for greater discrepancies between the presentation of visual and auditory stimuli, at least for the visual perception of movement. For example, Sekuler, Sekuler, and Lau (1997) conducted a study where two identical objects moved across a computer screen toward each other, coincided (i.e., continuous motion, pause for 1 frame, or pause for two frames), and then moved apart. Either no sound was presented during the trial or a sound was presented 150 ms before, during, or after the coincidence. The objects could be perceived as either continuing to move in their original directions after coincidence or as having collided with each other and reversing directions. Participants were exposed to each stimulus combination 20 times, in a random order. The authors found that even if the sound was presented 150 ms before or after the coincidence (i.e., asynchronous presentation), participants were more likely to perceive the objects as having collided and reversed directions than when no sound was presented (Sekuler et al., 1997). In another study, Stone et al. (2001) presented visual and auditory stimuli in asynchronous temporal windows. They found that participants felt the stimuli were presented synchronously when the auditory stimuli were presented

20 ms before and up to 150 ms after the visual stimuli. Therefore, it seems that in some contexts the temporal window can be wider than initially thought and could be task-dependent (van der Stoep, Postma, & Nijboer, 2017).

1.2.1.2 Spatial Principle. Prior studies have suggested that stimuli are more likely to be integrated in a multisensory manner if they are presented close together in space (i.e., spatial principle) (Alais et al., 2010; King & Palmer, 1985; Klasen et al., 2012, Meredith & Stein, 1986a). Similarly to the temporal principle, when stimuli are aligned in space, a coherent representation of the environment is created, which allows individuals to respond faster and more appropriately to it (Stein & Meredith, 1990). The brain occasionally receives conflicting information from different senses, which can lead to perceptual illusions and to one sense biasing or dominating another (van der Stoep et al., 2017). An example is the ventriloquism effect, where visual information biases auditory information (Bertelson & Aschersleben, 1998; Sarlat, Warusfel, & Viaud-Delmon, 2006; Spence & Squire, 2003). In other words, auditory stimuli are perceived as coming from the same location as visual stimuli, even if they are physically coming from two distinct locations. Vision can also bias tactile or proprioceptive information. For instance, if an individual lifts two objects of the same weight, but with two different volumes, he or she will perceive that the object with the smallest volume is lighter than the one with the larger volume (Cross & Rotkin, 1975; Ellis & Lederman, 1993). Vision seems particularly important to interpret conflicting information in spatial tasks and to give meaning to experiences (Ernst & Bülthoff, 2004).

Although vision is important for perception, it does not always dominate (Ernst & Bülthoff, 2004). Depending on the task, another sense may dominate if the information it provides is more precise. For example, hearing seems to dominate when the task requires a temporal judgment, as it provides more precise information than vision (Ernst & Bülthoff, 2004). When one light flash and several sounds are presented, the light flash can be perceived as several light flashes. This perceptual illusion is stronger when the delay between the light flash and the sounds is 100 ms or less (Shams, Kamitani, & Shimojo, 2002). In addition, when the temporal window is small (i.e., less than 40 ms), auditory stimuli are perceived before visual stimuli (Kanabus, Szelag, Rojek, & Poppel, 2002). Another study showed that when a visual stimulus was preceded by an auditory stimulus, the visual stimulus was perceived significantly faster; but if it was followed by the auditory stimulus, it was perceived significantly later (Fendrich & Corballis, 2001). These results suggest that hearing can dominate vision (i.e., the auditory information can bias the visual information) when a temporal judgment is required.

In short, two important principles of multisensory integration have emerged from the scientific literature: (1) the temporal principle (i.e., multisensory stimuli are more likely to be integrated in a multisensory manner if they are presented closely in time) (Alais et al., 2010; Klasen et al., 2012; Spence & Squire, 2003), and (2) the spatial principle (i.e., multisensory stimuli are more likely to be integrated in a multisensory manner if they are presented closely in space) (Alais et al., 2010; King & Palmer, 1985; Klasen et al., 2012, Meredith & Stein, 1986a).

1.3 Explicit Information Processing

1.3.1 Believable. If sensory stimuli are temporally and spatially congruent, their coherence (logical congruence, i.e., whether the stimuli "make sense") will be assessed through more explicit information processing. Whether stimuli will be considered coherent also depends on an individual's previous experience and expectations. Skarbez, Brooks, and Whitton (2017, 2018, 2020) and Skarbez, Neyret, Brooks, Slater, and Whitton (2017) used the term "coherence" to refer to the realism and fidelity of a virtual environment (VE), which contribute to the illusion that the events occurring in a VE are actually occurring (plausibility illusion, Psi; a more in-depth discussion will follow in the section "Subjective Experience"). The authors argued that a VE is coherent if it has an internal logical and behavioral consistency and matches user expectations and previous experiences. A VE does not need to exactly represent the physical environment to have a high level of coherence. Similarly, Gilbert (2016) used the term "authenticity." A VE will have high authenticity if the "affordances and simulations chosen in its implementation" respect user expectations based on their experiences in the physical environment and their intentions in the VE. Although the authors used the terms "coherence" and "authenticity" in the context of VR, they seem applicable to the physical environment as well. When stimuli are assessed as coherent, different perceptual illusions can be induced (e.g., experimentally induced body illusions).

1.3.1.1 Experimentally Induced Body Illusions. Multisensory integration plays an important role in body representation and body ownership. In this section, different experimentally induced body illusions and the conditions necessary to induce them are presented to prepare the context for immersions in VR and for our model on information processing and presence. These body illusions are examples of perceptual illusions that can be induced both in the physical environment and in VR (e.g., IJsselsteijn, Kort, & Haans, 2006). Body illusions are also examples that show that the temporal and the spatial principles and coherence can be important for inducing perceptual illusions.

Body representation provides information on the shape of body parts and their spatial location to distinguish what is and is not part of our body (Proske & Gandevia, 2012). Body ownership is the feeling that our body is ours (Proske & Gandevia, 2012). The manipulation of visual and tactile or proprioceptive stimuli can lead to body illusions. The rubber hand illusion and the full-body illusion are commonly referred to as body ownership illusions. The most studied illusions include, among others, the rubber hand illusion (the illusion that a rubber hand is our own), the full-body illusion (the illusion that an artificial body is our own), the body swap illusion (the illusion of exchanging our body with that of another individual), and the enfacement illusion (the illusion that the face of another individual is ours) (Serino et al., 2013). Numerous studies have shown that when multisensory integration is manipulated, individuals can appraise these body ownership illusions as believable.

1.3.1.1.1 Rubber Hand Illusion. Botvinick and Cohen (1998) were the first to report the rubber hand illusion paradigm. To induce this illusion, the participant's physical hand was placed out of sight under a table and a rubber hand was placed on the table where the participant's physical hand should be. Participants were assigned to one of the following two conditions: (1) synchronous stroking of the rubber hand and the physical hand with a paintbrush, or (2) asynchronous stroking of the rubber hand and the physical hand with the paintbrush. If the stroking was synchronous, participants felt that the rubber hand was their own and that they could feel the stroking of the rubber hand. The results showed that the illusion was induced in those who received the synchronous stroking, but not in those who received the asynchronous stroking (Botvinick & Cohen, 1998). These results suggest that a small temporal window between visual and tactile stroking of the physical hand and the fake hand is important to induce the illusion (i.e., the illusion is believable). Other studies have found similar results (e.g., Ehrsson, Holmes, & Passingham, 2005; Ehrsson, Wiech, Weiskopf, Dolan, & Passingham, 2007). Usually, a window longer than 500 ms will not induce the illusion (Zoulias, Harwin, Hayashi, & Nasuto, 2016).

Synchronous visual and tactile stroking is not a sufficient condition to induce the rubber hand illusion (Tsakiris & Haggard, 2005). Additional conditions must be met, to a certain extent, for the rubber hand illusion to be induced. The fake hand must have a realistic orientation and handedness. For example, it cannot be placed at an angle of 180 degrees or be a right hand while the physical hand is a left one since this orientation and handedness are impossible (Maselli & Slater, 2013). Furthermore, the fake hand must resemble a physical hand (Tsakiris & Haggard, 2005) and be located near the physical hand (Lloyd, 2007; Preston, 2013). However, the rubber hand illusion is flexible. For instance, it is possible to induce it by using an inflated glove. It also works on other limbs (e.g., feet). The illusion will be stronger if the fake limb resembles the physical limb. The illusion can be induced even if the skin color of the fake hand is different from the participant's (Farmer, Tajadura-Jiménez, & Tsakiris, 2012) or if an arm is added and it is hairy or longer than normal (Caola, Montalti, Zanini, Leadbetter, & Martini, 2018). These results suggest that the visual realism of the rubber hand remains to some extent less important than the synchronous presentation of stimuli (temporal congruence) to induce the illusion. Furthermore, these studies suggest that spatial congruence (i.e., the fake hand is near the participant's physical hand) and coherence (logical congruence) between the visual and tactile or proprioceptive stimuli (i.e., when the participant sees the fake hand being stroked, his or her physical hand is also being stroked) helps increase the believability of the illusion.

1.3.1.1.2 Full-Body Illusion. The full-body illusion can be induced in the physical environment (with cameras) or in VR. The procedure for inducing it is similar to the one for the rubber hand illusion (see Petkova & Ehrsson, 2008 and Slater, Spanlang, Sanchez-Vives, & Blanke, 2010 for a detailed procedure). The synchronous presentation of stimuli and the first-person perspective (egocentric) are important to induce the full-body illusion in the physical environment and in VR (Aspell, Lenggenhager, & Blanke, 2009; Petkova & Ehrsson, 2008; Petkova, Khoshnevis, & Ehrsson, 2011; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). If the third-person perspective (allocentric or from a bird's-eye view) is used, participants will feel that the event is happening to someone else rather than to them. In other words, they will feel like they are seeing someone else instead of themselves (Ehrsson, 2007). If the illusion is induced in VR, it is stronger if the virtual body or mannequin resembles the physical body. For example, the illusion is less strong if participants see a noncorporeal object (Lenggenhager, Tadi, Metzinger, & Blanke, 2007). However, the full-body illusion is also flexible. For instance, one study found that the illusion could be induced by using an invisible body (Kondo et al., 2018). These studies suggest that temporal and spatial congruence and coherence between the visual and tactile or proprioceptive stimuli helps increase the believability of the illusion. In other words, when the participant sees the virtual abdomen being stroked, his or her physical abdomen is also synchronously being stroked and the virtual abdomen is aligned with his or her physical abdomen.

In summary, multisensory integration plays an important role in inducing body illusions. It appears that presenting the stimuli within a small temporal window is more important to induce these illusions than high visual realism.

1.3.1.2 Multisensory Integration of Emotions. In this section, the multisensory integration of emotions is discussed, including the importance of the presentation of coherent (logically congruent) stimuli. This section will help prepare the context for our model on information processing and presence where coherent stimuli are a key component for inducing high presence.

Similarly to sensory stimuli, emotional stimuli are integrated in a multisensory manner (Klasen et al., 2012). The coherence of stimuli is important in the processing of emotions. For example, when individuals are exposed to a phobogenic stimulus (such as a dog, in a case of dog phobia), their brain receives visual (e.g., appearance of the dog) and auditory (e.g., barking and growling) information that induce fear. However, if their brain receives conflicting or incoherent information (e.g., seeing a dog, but hearing a different animal), they might feel less or not fearful. Another example is an individual suffering from aviophobia taking a plane. His or her brain receives proprioceptive (e.g., turbulence), olfactory (e.g., bad smell in the air), visual (e.g., concern of other passengers), and auditory (e.g., conversations of other passengers) information, which jointly contribute to provoke fear. If the stimuli are believable (coherent), the individual with a phobia is more likely to be fearful of the object, animal, or situation. In short, the brain processes and integrates multisensory stimuli, producing an emotional response.

1.3.1.2.1 Example. Many studies that have examined the multisensory integration of emotional stimuli have experimentally manipulated facial expressions and speech (Klasen et al., 2012). Coherent emotional audiovisual stimuli seem to be useful to identify emotions faster and more accurately than a visual or auditory stimulus presented alone. In one experiment (i.e., Collignon et al., 2008), participants were presented several blocks (randomly interleaved) of emotion expressions using (1) visual alone (video clips without any sound), (2) auditory alone (only the sound from the video clips), (3) congruent audiovisual (match between visual and auditory stimuli), or (4) incongruent audiovisual stimuli (mismatch between visual and auditory stimuli). Their task was to categorize the expressions as fear or disgust. The results showed that the participants categorized the expressions faster and more accurately when they were presented the congruent audiovisual stimuli than the visual alone or auditory alone stimuli. Interestingly, the results also showed that the participants relied on the visual stimuli to categorize the expressions when the incongruent stimuli were presented. However, when the reliability of the visual stimuli diminished in the incongruent blocks (i.e., added noise/static to the video clips), the results indicated that the participants relied on the auditory stimuli to determine whether the expression presented was fear or disgust. These findings suggest that vision can dominate when completing perceptual tasks, but also when completing emotional tasks. The authors concluded that congruent stimuli helped the participants categorize the emotion expressions, and that visual dominance appeared to be situation dependent. As we will see later on, the integration of coherent stimuli offers an explanation for people's reactions during VR immersions.

2 Multisensory Integration in Virtual Reality (VR)

Most studies examining multisensory integration and the perceptual illusions that can be induced have been conducted in the physical environment (as opposed to in a virtual environment [VE]). In addition, several of them used light flashes as visual stimuli and clicks as auditory stimuli (e.g., Shams et al., 2002). As a result, they may lack ecological validity. It would be interesting and necessary to study these effects in virtual reality (VR) and to use different stimuli. VR can be defined as a set of computer technologies offering an immersive environment, allowing the user to feel present and interact with this other reality in real time (Wiederhold & Bouchard, 2014). Benefits of VR include being able to expose users to realistic scenarios—that are dangerous or not feasible to study in the physical environment—in a safe and controlled environment and to simulate tasks that involve costly equipment (Aguinas, Henle, & Beaty, 2001). In this section, two topics are covered: (1) perceptual illusions induced in VR, and (2) models explaining how these illusions are induced. The main objective of this section is to explain the relationship between multisensory integration and VR and to prepare the context for presence, which is a perceptual illusion induced in VR and the main component of our model. The relationship between multisensory integration and presence is then described.

Globally, research suggests that the process of integrating stimuli from a VE and the physical environment is similar. When the brain receives conflicting information from different senses, perceptual illusions can be induced (van der Stoep et al., 2017), similar to those in the physical environment. For example, visual information can bias vestibular information in VR. When individuals are immersed in VR, they may have the perception of movement (Lécuyer, 2017), even if the physical environment is not moving. They may have this impression since the VE updates itself visually according to their head movements and the movements they make with the controllers, but their physical body remains in the same location. This mismatch can lead to cybersickness (Allison, Harris, Jenkin, Jasiobedzka, & Zacher, 2001; McCauley & Sharkey, 1992), which resembles motion sickness in the physical environment. Research shows that a delay of a few ms between stimuli in the VE can be perceived by users and affect their experience. For instance, researchers suggest that a delay of 17 ms or more between visual stimuli and participants' head movements in a VE will be perceived (Adelstein, Lee, & Ellis, 2003). In another study, Meehan, Razzaque, Whitton, and Brooks (2003) compared the effect of an added delay of 50 ms and of 90 ms on presence in an anxiety-provoking VE. Self-report data from164 participants were analyzed and the results showed that presence was lower in the condition with the added delay of 90 ms. These results suggest that the temporal principle (Alais et al., 2010; Klasen et al., 2012; Spence & Squire, 2003) also applies to VR, and that delays are detrimental to presence. In addition, studies have shown that the presentation of visual and tactile or proprioceptive stimuli should be synchronous to induce body illusions in VR (e.g., Ehrsson et al., 2007; González-Franco, Peck, Rodríguez-Fornells, & Slater, 2014; Lenggenhager et al., 2007). These results suggest that individuals integrate multisensory information from VEs and the physical environment in a similar way. In other words, it is important for stimuli to be presented close together in time to be integrated in a multisensory manner in VR. If there is a delay between virtual stimuli, the users' response in the VE should be similar to their response in the physical environment.

2.1 The Role of Multisensory Integration in Inducing Perceptual Illusions in VR

Although multisensory integration theories exist in Neuroscience and Psychology, there are few specific to VR. Riva et al. (2018) and Riva, Wiederhold, and Mantovani (2019) proposed that VR is effective in assessing and treating various health problems since it creates embodied simulations of the body thanks to the multisensory information received and integrated by the brain. These simulations make it possible to predict and represent the actions and emotions of users. For users to feel present, the body simulation created by the technological system must update according to the users' movements in the VE and must provide the expected sensory information to the brain. For example, there should be no discrepancy between the users' head movements and the visual changes perceived in the head-mounted display. This theory is interesting to explain how the brain processes virtual multisensory information related to embodiment and how users immersed in VR come to feel and act as if they are actually in the VE and no longer in the physical environment (e.g., in a laboratory). This is known as presence, or more specifically, the perceptual illusion of "being there" in the VE (Heeter, 1992).

Gonzalez-Franco and Lanier (2017) proposed a neuroscientific model, inspired by previous research, to explain how illusory experiences are induced in VR. Their model has three components: (1) bottom-up multisensory processing (Blanke, 2012; Calvert, Spence, & Stein, 2004), (2) sensorimotor self-awareness frameworks (Gallagher, 2000), and (3) top-down prediction manipulations (Haggard, Clark, & Kalogeras, 2002).

Bottom-up multisensory processing (Blanke, 2012; Calvert et al., 2004) refers to the strategy used by the brain to integrate sensory stimuli received from multiple senses (Gonzalez-Franco & Lanier, 2017). If the stimuli received are temporally congruent and coherent (logically congruent), the brain will be more likely to appraise them as correct, whereas if they are temporally incongruent and incoherent, the brain could "disregard" one of the stimuli, appraising it as being "incorrect" (e.g., if there is a delay between a virtual character's lip movements and the words that he is pronouncing: the brain could "disregard" the visual stimulus to understand the words pronounced).

Sensorimotor self-awareness frameworks (Gallagher, 2000) refer to the comparisons made by the brain between the multisensory stimuli it has received and the predictions it has made about the actions that should occur (Gonzalez-Franco & Lanier, 2017). For instance, if the users move their head and the VE adjusts to their head movements, they will feel a stronger VR illusion compared to if there were several delays in the tracking of their head movements. Similarly, if they extend their virtual hand by 10 cm to touch a virtual wall, the illusion will be stronger if they visually perceive that the contact with the virtual wall is made at 10 cm than if it is made at 5 cm (and consequently they are unable to touch the virtual wall) or at 15 cm (and their virtual hand consequently passes through the virtual wall). When multisensory stimuli correspond to the anticipated actions, the users will likely feel a strong VR illusion.

Top-down prediction manipulations (Haggard et al., 2002) allow some flexibility to the illusion. The user will feel a strong VR illusion if the multisensory stimuli received match the predictions made by the brain based on the user's previous experience and expectations (Gonzalez-Franco & Lanier, 2017). For instance, if there is a delay of a few ms between two virtual stimuli (a lightning flash and the sound of thunder), a user may be perceived as simultaneous or not depending on previous experience in the physical environment and in VR.

2.2 Subjective Experience

2.2.1 Presence. The product of these integration processes will lead to users subjectively feeling as if the experience is actually occurring and as if they are actually in the place depicted in the VE (Slater, 2009, 2018; Slater, Spanlang, & Corominas, 2010). Three models of VR (i.e., Lombard & Ditton, 1997; Gonzalez-Franco & Lanier, 2017; Riva et al., 2018; Riva et al., 2019), which seem to complement each other well, explain how information processing leads to presence, and why users react as if they were actually in the VE. Lombard and Ditton (1997) claim that when users feel present, they "forget" that they are immersed in a VE and that their experience is created by a medium (VR equipment). Gonzalez-Franco and Lanier (2017) explain that multisensory integration leads to various illusions in VR. Riva et al. (2018) and Riva et al. (2019) suggest that embodiment is important to feel present in a VE.

Lombard and Ditton (1997) proposed that presence is a perceptual illusion of non-mediation: users believe that they are in another reality and act accordingly without perceiving or recognizing that this illusion is created by technology (i.e., that they are immersed in VR). In other words, the brain is fooled, and users "forget" that the experience in the VE is created by technology. Users feel present, or like they "are there" in the VE (Heeter, 1992). This is interesting because many (if not most) individuals tend to respond to stimuli in the VE, even though they are consciously aware that they are not physically in that location (Slater, 2003). For example, users will duck to avoid an object flying toward them (Sanchez-Vives & Slater, 2005), and will often walk around a pit instead of over it, even if they know that they will not fall in the physical environment (e.g., Meehan, Insko, Whitton, & Brooks Jr, 2002; Meehan et al., 2003; Sanchez-Vives & Slater, 2005; Slater, Usoh, & Steed, 1995; Usoh et al., 1999). Individuals will often mention after an immersion in VR that they consciously knew that the experience was not real, but they still responded as if it had been.

There appears to be few neuroscientific and information processing models that focus specifically on presence and multisensory integration in VR. As we have started to see above in this article, Riva et al. (2018) and Riva et al. (2019) presented a model to explain the relationship between embodiment and presence in VR. Their model is interesting because it shows the importance of the interaction between the user's actions, the VE's responses, and the sensory information received by the brain. Immersion in VR is a rich and rapid interactive process between the user and the technological system, which must update the body simulation it created according to the user's actions in the VE and provide the expected sensory information to the brain (Riva, Mantovani, & Bouchard, 2014). Riva et al.'s (2018) and Riva et al.'s (2019) model could be extended by including a discussion of the relationship between multisensory integration principles and presence (see the section "A Novel Integrated Information Processing Model of Presence"). Gonzalez-Franco and Lanier's (2017) model explains well how different perceptual illusions are induced in VR. A more explicit description of the relationship between multisensory integration and presence could be an interesting addition to their model. The following paragraphs delve into the details of their model and attempt to explain the relationship between multisensory integration and presence using their model. As we mentioned previously, Gonzalez-Franco and Lanier's (2017) model comprises three components: (1) bottom-up multisensory processing (Blanke, 2012; Calvert et al., 2004), (2) sensorimotor self-awareness frameworks (Gallagher, 2000), and (3) top-down prediction manipulations (Haggard et al., 2002).

The first component of their model stipulates that multisensory stimuli are processed in a bottom-up manner (Blanke, 2012; Calvert et al., 2004). Stimuli can be presented in a VE involving multiple senses (e.g., visual, auditory, tactile, proprioceptive, olfactory) and the brain must integrate them (Gonzalez-Franco & Lanier, 2017), which can impact presence. Slater (2009, 2018) and Slater, Spanlang, and Corominas (2010) argued that presence has two components: the place illusion (PI—the feeling of "being there" in the VE) and the plausibility illusion (Psi—the feeling that the events in the VE are actually occurring) and therefore behaving accordingly. Users will tend to respond to stimuli in the VE implicitly, even if they consciously know they are in the physical environment (e.g., in a laboratory) (Sanchez-Vives & Slater, 2005; Slater 2003; Slater & Usoh, 1993). For example, when they see a table in a VE, they will tend to naturally walk around it instead of through it, even if they know that there is no physical table in the room. The presentation of well synchronized and coherent multisensory stimuli can contribute to the feeling that the events in the VE are actually occurring (the plausibility illusion) and user behavior (Gilbert, 2016; Skarbez, Brooks, & Whitton, 2017, 2018, 2020; Skarbez, Neyret, et al., 2017; Slater et al., 2009, 2018; Slater, Spanlang, & Corominas, 2010), as these stimuli increase the believability of the VE (i.e., the VE makes sense to the user). The believability of the VE and the feeling that the scenario is actually occurring in turn increase the feeling of "being there" in the VE (the place illusion).

Gonzalez-Franco and Lanier's (2017) model then states that the brain makes comparisons between the multisensory stimuli it has received and the predictions it has made about the actions that should occur, which are referred to as sensorimotor self-awareness frameworks (Gallagher, 2000). In other words, when multisensory stimuli match the predicted actions, the brain will be more likely to be fooled and the user will be more likely to feel high presence. For instance, if users (who expect a VE to respect the laws of physics) drop a plate on the floor in the VE and it breaks, they will feel higher presence than if the plate had not broken since they expected it to break, as it would in the physical environment. It is possible that the plausibility illusion leads to the place illusion. In other words, when the VE appears believable, users will feel like the scenario depicted in the VE is actually occurring and respond to stimuli implicitly and will subsequently draw a conclusion about where they are. When the VE reacts appropriately to their actions based on their expectations and previous experience (e.g., if users drop a virtual plate on the virtual ground, it breaks), they will feel as if they "are there" in the VE.

Finally, Gonzalez-Franco and Lanier's (2017) model specifies that top-down prediction manipulations (Haggard et al., 2002) allow some flexibility to illusions in VR. Therefore, even if the visual realism of a VE is reduced, presence may be high since the VE can still represent a physical situation in a realistic way. In other words, if the plausibility illusion is induced, then the place illusion can also be induced. A user can feel as if he or she is "really" in the VE since the VE remains believable. It does not need to identically resemble the physical environment. Indeed, research has suggested that visual realism is important to a certain extent to increase presence (e.g., Hvass et al., 2017a, 2017b), but presence can remain elevated even if visual realism is reduced. For example, in one study, Dinh, Walker, Hodges, Song, and Kobayashi (1999) studied the effect of visual realism and multisensory stimulation on presence and memorization in VR in 322 participants. The participants were randomly assigned to one of sixteen conditions where visual realism was either high (high-resolution textures and local lighting) or reduced (the resolution of the textures was reduced to 25% of the high-resolution textures and ambient lighting), with or without auditory (ambient sounds), olfactory (aroma of coffee), and tactile (wind and temperature changes) stimuli. They were immersed in a virtual office, which included a small and a large office, a copier room, a reception area, a hallway, a bathroom, and a balcony. The results showed that the addition of auditory, tactile, and olfactory stimuli increased participants' presence and their memorization of the VE. The improved visual realism did not increase their presence or their memorization of the VE. This could be due to the VE still being believable and representing a scenario that could be encountered in the physical environment. In short, the brain appears to integrate virtual stimuli in a similar way to stimuli from the physical environment but will have some flexibility. Provided the VE looks believable (even if it does not exactly resemble the physical environment), users can feel like they "are there" in the VE.

As temporal windows are important for inducing perceptual illusions and for integrating multisensory information, they are likely also important for inducing presence. When virtual stimuli are temporally congruent and coherent, the brain will be fooled into appraising the experience in the VE as believable and actually occurring (plausibility illusion, Gilbert, 2016; Skarbez, Brooks, & Whitton, 2017, 2018, 2020; Skarbez, Neyret, et al., 2017; Slater et al., 2009, 2018; Slater, Spanlang, & Corominas, 2010), which will lead to the feeling that one is actually in the VE (place illusion). It is possible that a significant delay between virtual stimuli (e.g., visual and proprioceptive stimuli) may decrease or break presence (plausibility and place illusions). For instance, if a VE does not update itself when users move their head, presence could be reduced or broken. If users no longer feel present or feel less present in a VE that represents the physical environment, they could react differently in the VE than they would in the physical environment (e.g., walking through virtual walls) since the believability of the VE is reduced. In other words, if the plausibility illusion is reduced or not induced, the place illusion (the feeling of "being there" in the VE) will be reduced or not induced either. Unfortunately, to the authors' knowledge, the relationship between the temporal windows for multisensory integration and presence (including plausibility and place illusions) has not yet been studied.

2.3 A Novel Integrated Information Processing Model of Presence

In this section, a novel integrated information processing model in VR is proposed based on the elements of these three models, and Slater's plausibility and place illusions (Slater, 2009, 2018; Slater, Spanlang, & Corominas, 2010). In this model, we posit that virtual and/or somatosensory stimuli (input) are first received by the senses and integrated by the brain through implicit information processing (i.e., core information processes occurring very rapidly and without awareness). The conclusion of the integration of the stimuli will depend on a user's previous experience and expectations, and if they match with what is predicted by the sensorimotor system. If the sensorimotor stimuli are congruent with what is expected, they will be processed as believable through more explicit information processing. Whether stimuli will be considered believable will also depend on a user's previous experience and expectations (Gilbert, 2016; Skarbez, Brooks, & Whitton, 2017, 2018, 2020; Skarbez, Neyret, et al., 2017; Slater et al., 2009, 2018; Slater, Spanlang, & Corominas, 2010), and through bottom-up and top-down conception matching processes that are characterized by more explicit information processing (Gonzalez-Franco & Lanier, 2017). When stimuli are assessed as believable, a user will further experience embodiment and agency in the VE (Riva et al., 2018; Riva et al., 2019). The product of these dynamic processes will lead to subjectively feeling as if the experience is actually occurring. This is the subjective experience of the plausibility illusion described by Slater (2009, 2018) and Slater, Spanlang, and Corominas (2010). The user can subsequently also believe that he or she is actually in the place depicted in the VE (i.e., the second component of presence according to Slater: the place illusion). The subjective meaning given to the place and the objects experienced in the VE will impact the user's behavior, which in turn will further influence which stimuli in the sensory input loop will be processed and integrated by the brain. The proposed model is explained in more detail in the following paragraphs and illustrated in Figure 1. Suggestions for future research are also discussed.

2.3.1 Input (Sensory Information). The proposed model states that the senses first receive sensory information from virtual and/or somatosensory stimuli (if the immersion is not complete, the senses will also receive sensory information from the physical environment). Information is then processed and integrated in the corresponding sensory areas of the brain.

2.3.2 Implicit Information Processing.

2.3.2.1 Multisensory Integration (Contingencies Match). The brain will compare the information received to what is normally expected, based on previous experience (Gonzalez-Franco & Lanier, 2017). Based on previous experiences in the physical environment and in VR (if the individual has previously been immersed in VR), the brain expects temporal congruency between all

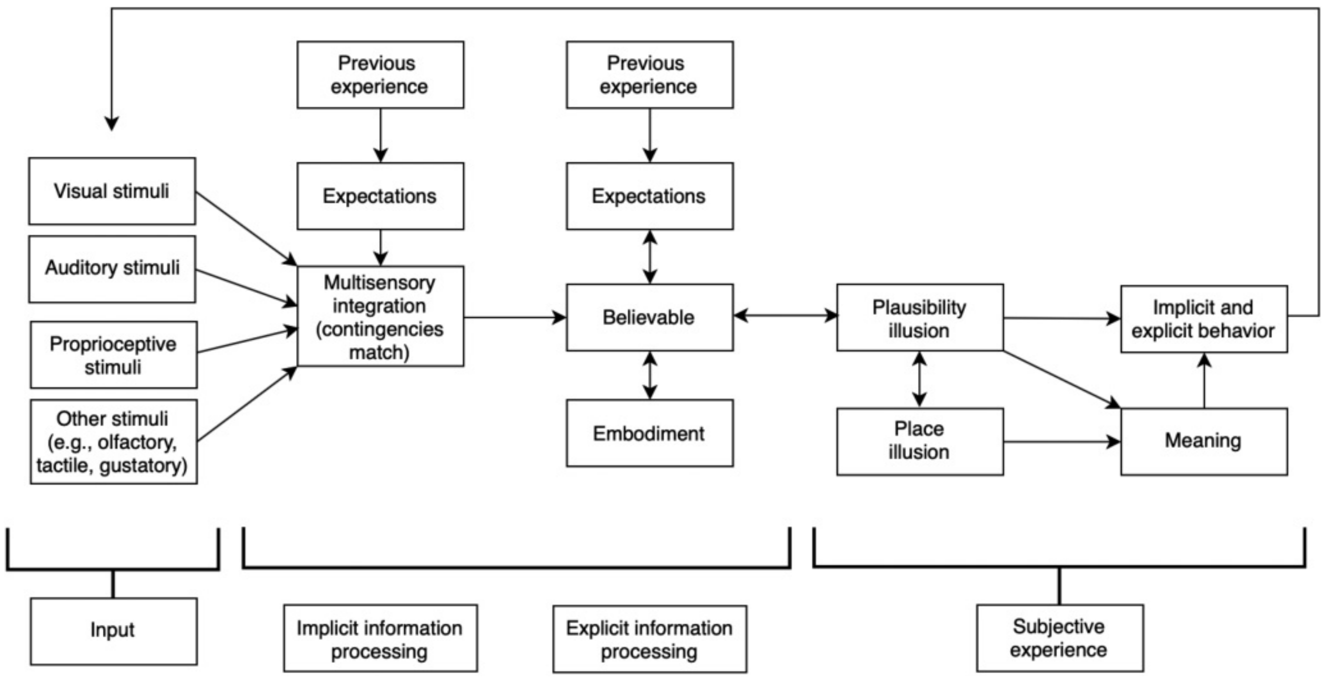

Figure 1. *Conceptual model of information processing that leads to presence. The visual, auditory, proprioceptive, and other stimuli include virtual and somatosensory stimuli (if the immersion is not complete). The box containing "Multisensory Integration" includes the number of senses stimulated, the temporal windows between the stimuli, and the spatial location of the stimuli.*

relevant stimuli, including visual, auditory, proprioceptive, and sensorimotor stimuli (Alais et al., 2010). As we have seen above in this article, this normal information processing applies *in vivo* as well as in VR. If there is a small yet significant delay between stimuli, individuals will perceive them as two separate events (Keetels & Vroomen, 2012). This multisensory integration processing is implicit: individuals do not consciously realize that it is occurring and cannot verbalize what is occurring because such a delay is rapid and automatically processed (refer to the introduction for more details about temporal windows and synchronicity). If the delay is too long or the spatial location too discrepant to support a coherent multisensory integration, it can be consciously detected and integration will not occur (Alais et al., 2010; Keetels & Vroomen, 2012; Klasen et al., 2012). Some temporal mismatch can lead to unwanted negative side effects (commonly referred to as cybersickness; Allison et al., 2001; McCauley & Sharkey, 1992) and still lead to the conclusion that the experience is believable if the overall meaning of the stimuli is not too ambiguous to be coherent. If multisensory integration fails, the experience will not be appraised as believable and will significantly limit presence.

2.3.3 Explicit Information Processing.

2.3.3.1 Believable. Once the sensory information has been integrated as temporally and spatially congruent, the brain will appraise the believability of the overall experience. The ongoing information processing becomes more explicit and continues to rely on a conception matching process where the flow of sensory information is integrated compared with expectations based on previous experience. Templates of previous experience are more complex than at the implicit level and involve behaviors and properties of objects and characters from the physical environment (Gilbert, 2016) and from the VE itself (i.e., the internal logical consistence or coherence of the VE) (Hofer, Hartmann, Eden, Ratan, & Hahn, 2020; Skarbez, Brooks, & Whitton, 2017, 2018, 2020;

Skarbez, Neyret, et al., 2017; Slater et al., 2009, 2018; Slater, Spanlang, & Corominas, 2010). The bottom-up and top-down processes of the currently experienced situation are expected to match internal representations of the physical environment and of the VE. In VR, a VE will be appraised as believable when the sensory information is congruent (temporally and spatially) and coherent (logically congruent) and matches expectations about the appearance and behavior of virtual objects or characters (Gonzalez-Franco & Lanier, 2017). In a pilot experiment, Slater and Usoh (1993) found that many participants felt reduced presence because the VE did not respect the laws of physics (e.g., participants could walk through walls, gravity only partially worked) and moving in the VE was not "natural" (i.e., using a mouse instead of physically walking). Some participants mentioned being disappointed that when objects fell to the ground from a height, they did not break or produce a corresponding sound. The authors suggested that participants expected the VE to match the physical environment, and when it did not, there was a mismatch between their expectations and their experience in the VE, which resulted in lowered presence. In other words, participants could have felt reduced presence because the VE was not believable.

In a qualitative experiment, Ghani, Rafi, and Woods (2019) immersed 20 participants in a VE that replicated a physical mosque and some of its surroundings situated in a city in Malaysia. The VE contained animated avatars and ambient sounds. During interviews, some participants who had visited the physical mosque reported that its virtual version was "slightly unrecognizable" as its surroundings lacked certain details from the physical environment. Although this experiment is qualitative, the results suggest that a user's previous experience in the physical environment can impact the believability of a VE and thus the plausibility and place illusions. In other words, the mismatch between some of the participants' past memories (and expectations) and their experience in the VE diminished their feeling of "being there" at the mosque (place illusion) due to decreased believability and feeling that the experience was actually occurring (plausibility illusion). An encounter with a virtual cat (where a user expects to be immersed in a VE that resembles the physical environment) can be used as another practical example. If the input information is based on coherent virtual visual information (e.g., a virtual black animal shaped like a cat) and auditory information (e.g., meowing), information processing will lead to the conclusion that the object is a cat. On the other hand, if the information processed is incoherent with a priori expectations (e.g., a virtual black animal shaped like a cat that barks), the conclusion will likely be to appraise the virtual object as not very believable. If the same situation is experienced in a pet-store, the incoherency could be dismissed and assumed to come from another animal in the room. If the same situation is experienced by a person suffering from a cat phobia, the perceived threat may be high enough to warrant dismissing incoherent situations in favor of protecting oneself from danger. For instance, if a virtual black quadruped shaped like a cat that meows is encountered in a VE representing the surface of the moon, the phobic might react with fear despite that believability can still be appraised as low. This information processing clearly involves more explicit and complex integration than the automatic integration of multisensory information. The study conducted by Usoh et al. (1999) is another example that suggests the believability of an experience can influence presence. The authors found that participants felt higher presence when they physically walked from one virtual room to another than when they walked-in-place (i.e., they did not physically walk, but instead moved their head in the direction that they wanted to go and their virtual body walked there) or when they flew (i.e., same procedure as walking-in-place, but they flew to the location). It is probable that participants expected to be able to travel the same way in the VE as they would in the physical environment and thus felt reduced presence in those conditions as humans physically move to reach a destination and cannot fly in the physical environment (except if they are traveling in a vehicle that can fly).

A believable VE will also influence the processing of further immersions in VR and change expectations of how a VE should look like and respond (Gonzalez-Franco & Lanier, 2017). For example, if users were exposed to a believable large spider that walks in a particular way in a VE, they might expect spiders to look and respond in that same manner in another VE containing spiders, or in the same VE at a different time. Another example is if users were immersed in a believable VE where they have three arms, they could expect to have three arms in a different VE or in the same VE at a different time. What is experienced in VR can be significant enough to create the illusion of additional limbs (e.g., Won, Bailenson, Lee, & Lanier, 2015). Won, Bailenson, Lee, and Lanier (2015) immersed participants in a VE where they had to hit cubes displayed in three locations in front of them. One location was farther away from them and that cube could be hit by moving forward to reach it. Instead of moving forward, participants in the third limb condition could reach the cube using a virtual third arm that was longer and articulated by rotating their wrists. Although the third limb was unrealistic, participants learned to control it and hit more cubes than when they had two arms. Interestingly, their performance also improved over time: they hit more cubes and at a faster rate during later trials than earlier ones. It seems that participants adapted and learned to use the third arm, despite the fact that they only had two limbs in the physical environment. In another study, Steptoe, Steed, and Slater (2013) examined whether participants could learn to control a virtual tail to block virtual green particle beams. Participants were assigned to either a condition where the tail moved synchronously with their physical hip movements or a condition where the tail moved asynchronously with their physical hip movements. They could block the particle beams with their hands or feet, but some of them were more easily reached with the tail. The results revealed that participants in the synchronous condition felt higher body ownership and agency of the tail than those in the asynchronous condition. Participants in the synchronous condition were also able to successfully control the tail and performed better than those in the asynchronous condition. Furthermore, their performance improved over time and in the final quarter of the game, they were able to better coordinate the movement of their hands and tail. These results support Won et al.'s (2015) and suggest that participants can adapt to having additional body parts, even though this is not possible in physical reality.

These examples illustrate that in VEs where contingency relationships are synchronous, and despite the conditions being unrealistic, the scenario can still be appraised as believable and can update existing expectations about how a VE should look and respond. These expectations are explicit at first and, with practice, become implicit through learning (e.g., participants had to think about the movements to control the third arm or the tail, but they were eventually able to automatically control them). These updated expectations about contingency relationships (e.g., if participants move their hips, the virtual tail will synchronously move) in turn affect believability (when they move their hips, the tail moves the way it is supposed to), presence (feeling like one is actually moving the tail and is in the VE), and behavior in the VE (moving the tail and using it to complete the task).

Interestingly, it seems possible to change participants' expectations by manipulating the instructions given to them. For instance, Bouchard, St-Jacques, Robillard, and Renaud (2008) exposed 31 participants with snake phobia to an anxiety-inducing VE and to a non-anxiety-inducing VE (randomly assigned order). The participants' task was to explore the VE (a desert). In the anxiety-inducing VE, participants were informed that there were poisonous, dangerous, and aggressive snakes hidden in the sand and that they would not attack them, but they should be on guard (the VE did not actually contain snakes). In the non-anxiety-inducing VE, participants explored the same environment, but were informed that there were no snakes (the VE did not contain any snakes either). Data from a verbal measure showed that although participants were not exposed to virtual snakes in either condition, their presence was higher when they *expected* to be exposed to them. During the debriefing, most participants verbally indicated that they behaved differently in the anxiety-inducing VE (i.e., they were not able to explore or control the VE because they were afraid of encountering a snake). It is possible that the expectation of encountering snakes coupled with being immersed in an environment where snakes could actually be found in the physical environment (i.e., a desert) increased the believability of the experience and participants' feeling that the events were actually occurring (plausibility illusion) and of being in the VE (place illusion), which affected their behavior. The results of this study seem to lend support to the hypothesis that participants' expectations have an effect on believability and on the plausibility and place illusions.

2.3.3.2 Embodiment. Embodiment (feeling like one's physical body is substituted by a virtual one, Spanlang et al., 2014) will also contribute to the explicit processing of information appraised as believable and is induced by sensory information relevant to the virtual body. The virtual body can be visible in the virtual space, in the form of an avatar, but it does not have to be. If when a user moves his or her physical body and the corresponding experience in the VE is consistent, the user can feel embodied (Riva et al., 2018; Riva et al., 2019). In the physical environment, one does not have to see one's own hand under the table to grab an object on the floor. The match with the proprioceptive experience and touching the object is enough to feel that it is our body in action. In VR, a match between interoceptive and somatosensory information on the physical body's location and actions, and the impact of the corresponding actions in VR will lead to embodiment when congruent with past experience (Haans & IJsselsteijn, 2012). Having a visible virtual body adds to this experience but is not essential. Temporal and spatial congruency and coherence (the stimuli must be believable) between visual and tactile or proprioceptive stimuli are required and sufficient to induce embodiment (Aspell et al., 2009; Botvinick & Cohen, 1998; Carey, Crucianelli, Preston, & Fotopoulou, 2019; Lloyd, 2007; Preston, 2013; Riva et al., 2018; Riva et al., 2019). Embodiment can also impact whether virtual stimuli are considered believable, and its role is highlighted at a later (explicit information processing) stage than the implicit multisensory integration. Embodiment involves the perception that the body belongs to the user and provides a sense of agency in the VE. It contributes to the believability of the experience and is also reinforced by a believable experience (Riva et al., 2018; Riva et al., 2019). For example, if users feel embodied, they feel like it is *their* head rotating to examine the surroundings and that *they* are moving in the virtual space.

2.3.4 Subjective Experience.

2.3.4.1 Plausibility Illusion (Psi). The resulting plausibility illusion (Psi) will be induced if the VE is believable based on the conception matching process described previously. This is what Slater (2009, 2018) and Slater, Spanlang, and Corominas (2010) refer to as the plausibility illusion (i.e., feeling that the events in the VE are actually occurring). If users appraise the virtual scenario as believable and actually occurring (e.g., a virtual cat walking on four legs and meowing instead of walking on two legs and speaking in English), their behavior in the VE will resemble or be identical to their behavior in the physical environment (e.g., they could pet the virtual cat, or run away if they are phobic). If users are instead immersed in a fantastical (and believable) VE, it is likely that their behavior will resemble their behavior from a previous immersion in that VE (e.g., if users were immersed in a fantastical VE where cats spoke in English and the users spoke to one, the users would probably speak to the cat again if it was encountered in a future immersion in that VE).

Furthermore, if the virtual scenario is experienced as actually occurring, it further strengthens the processing of stimuli as believable and matching with expectations (i.e., the plausibility illusion affects the concept "Believable") (Gilbert, 2016; Skarbez, Brooks, & Whitton, 2017, 2018, 2020; Skarbez, Neyret, et al., 2017; Slater et al., 2009, 2018; Slater, Spanlang, & Corominas, 2010). For example, if trainees are flying a virtual aircraft and feel that they are actually flying it, they will likely find that flying it is believable. Interestingly, the virtual aircraft does not need to exactly resemble a physical one to lead to positive training outcomes (Caro, Corley, Spears, & Blaiwes, 1984).

It is important to reinstate the distinction between the concept of processing information as "believable" and the plausibility illusion. Processing stimuli as believable refers to the process of comparing information with a priori templates of rules and a representation of the world and how it functions. The plausibility illusion refers to the consequent feeling that the events are actually occurring (i.e., the extent to which the virtual scenario is experienced as actually occurring) (Slater, 2009, 2018; Slater, Spanlang, & Corominas, 2010). The strength of the plausibility illusion will be related to how believable the VE is. It is important to note that a VE could be believable without necessarily being realistic: cartoonish looking furniture might not appear realistic, but a user may still walk around it to avoid colliding with it.

2.3.4.2 Place Illusion (PI). The place illusion (PI) will be induced if the users feel like the virtual scenario is actually occurring (plausibility illusion). When it is induced, users will feel like they are “really there” in the VE (Heeter, 1992) and “forget” that the VE is created by VR equipment (Lombard & Ditton, 1997). The users can be consciously aware that they are in the physical environment (e.g., in a laboratory), but also feel like they are actually in the VE (Sanchez-Vives & Slater, 2005; Slater 2003; Slater & Usoh, 1993). This is what Slater (2009, 2018) and Slater, Spanlang, and Corominas (2010) call the place illusion (the feeling of “being there” in the VE). If the users feel like the VE is unbelievable and that the virtual events are not actually occurring, then they will feel like they are in the physical environment and not in the VE. In other words, the strength of the place illusion will be associated with the strength of the plausibility illusion and the believability of the VE. If the users feel like the VE contains both some unbelievable and believable components based on their expectations, then the plausibility and place illusions could still be induced but should not be very strong. For instance, if they expect to be immersed in a virtual city that resembles a physical city and respects the laws of physics but realize that they can fly in the virtual version of the city, it is likely that they will feel like they are not actually flying in the city and feel a reduced sense of “being there” in the city. If the users feel like the VE is completely unbelievable based on their expectations (e.g., the users expect to be unable to walk through virtual doors and walls but discover that they must do so to move to the next room), then the plausibility and place illusions will likely be very low (i.e., the users will feel like they are not actually walking through walls and doors and like they are in the physical environment instead of in the VE). While the plausibility illusion impacts the place illusion, the reverse is also true: if users believe that they are actually in the VE, they will further feel like the scenario depicted in it is actually occurring.

Few studies have been conducted to specifically study the place and plausibility illusions. In one experiment, Skarbez et al. (2018) examined whether self-report measures could distinguish between the effects of the plausibility and place illusions (the results related to the physiological measures are not reported here, see their article for the full results). To study the plausibility illusion (Psi), the authors manipulated the levels of coherence, which were divided into two concepts (i.e., physical coherence and narrative coherence). Specifically, participants were informed that they needed to complete certain tasks to be able to move on to the next stage of the experiment. In the high Psi condition, the laws of physics applied (physical coherence) and the instructions were valid (narrative coherence), but in the low Psi condition, the laws of physics did not apply, and the instructions were false. To examine the place illusion (PI), the authors manipulated levels of immersion: either the head-mounted display had a field-of-view of 60° diagonal and spatial sound cues and passive haptics were added (high PI) or the head-mounted display had a field-of-view of 30° diagonal and no spatial sound cues or passive haptics were added (low PI). Thirty-two participants were randomly assigned to one of four conditions: (1) high PI-high Psi, (2) high PI-low Psi, (3) low PI-high Psi, or (4) low PI-low Psi. Participants completed five stages in the VE: (1) participants played a Simon-like memory game to familiarize themselves with the VE, (2) practice room where participants dropped balls into containers with a target, (3) office-like room where participants dropped balls onto targets, (4) pit-like room where participants dropped balls onto targets on the ground floor, and (5) participants returned to the first room and played the Simon game again. Participants completed the Witmer–Singer Presence Questionnaire (Witmer & Singer, 1998) and a modified version of the Slater–Usoh–Steed Presence Score (Usoh, Catena, Arman, & Slater, 2000) post-experimentation. The results showed that several subscales of the Witmer–Singer Presence Questionnaire seemed to distinguish between immersion and coherence and responded to higher levels of immersion as a main effect. The Slater–Usoh–Steed Presence Score appeared to respond to increased immersion as a main effect, and the scores were higher in the matched (low PI–low Psi and high PI–high Psi) than in the unmatched conditions (low PI–high Psi and low Psi–high PI). Neither questionnaire appeared to respond to increased coherence as a main effect. However, the total score on both questionnaires increased in the condition with high PI–high Psi. These results are interesting and suggest that in future research perhaps different measures should be used to measure the place and plausibility illusions and additional factors related to immersion and coherence could be manipulated.

2.3.4.3 Meaning. The meaning given to the place and the objects in the VE will affect the user's implicit (automatic, e.g., rotating one's physical shoulders to pass through narrow virtual doors, Lepecq, Bringoux, Pergandi, Coyle, & Mestre, 2009) and explicit behavior (conscious, e.g., confronting a feared stimulus, Emmelkamp et al., 2002). Two users who are immersed in the same VE could associate a different meaning to the place and the objects in the VE and therefore behave differently. For example, if a user who is suffering from acrophobia is exposed to a pit and feels that the scenario is actually occurring and that he or she is actually in the VE, that person will likely feel a high level of fear and avoid looking into it because it is perceived as a threat. On the other hand, a user who does not fear heights will likely be able to look into the pit—even if he or she feels the scenario is actually occurring and feeling actually in the VE—because the pit is not perceived as a threat. Avoiding collisions with virtual furniture could be another example of how two users could attribute a different meaning to a VE. Users who believe that they are in the VE and that the virtual events are actually occurring will likely implicitly avoid walking through virtual furniture because they believe that it is solid, and collisions with objects are normally avoided, as they would be in the physical environment. In contrast, users who experience remaining in the physical environment and that the virtual events are not actually occurring will likely walk through the virtual furniture because they believe that it is not actually there and that they cannot be harmed by a collision. If the plausibility and place illusions are sufficiently strong, users can derive meaning to the place and the objects in the VE, which will affect their behavior.

Empirical studies also appear to indicate that two users can give a different meaning to the same VE. In one study, Simon, Etienne, Bouchard, and Quertemont (2020) compared alcohol cravings of 18 heavy drinkers and 22 occasional drinkers following an immersion in a virtual bar with alcoholic beverages. The results revealed that the higher the perceived ecological validity (i.e., the feeling of believability, realism, and naturalness of the VE—this corresponds to the plausibility illusion), the higher the alcohol craving levels in heavy drinkers but not in occasional drinkers. The authors suggested that perceived ecological validity moderates the relationship between alcohol consumption in the physical environment and cravings following the immersion in the VE. These results suggest that the believability and perceived realism of the experience and of the VE led heavy drinkers to crave alcohol as they would in the physical environment. However, this was not the case in occasional drinkers since they do not attribute the same meaning to alcohol. In another study, Quintana, Nolet, Baus, and Bouchard (2019) found that the implicit perception of others' scent affected participants' perception and impression of an avatar in a virtual bar. The avatar did not speak or move and had a neutral facial expression. Specifically, the participants who were exposed to a fear-related scent felt more anxious, which led to reduced interpersonal trust toward the avatar compared with participants who were exposed to a joy-related scent (between-subjects design). These results show that participants attributed a different meaning to the avatar in the VE (i.e., he is threatening or not), which affected their anxiety levels and their level of interpersonal trust.

A user could attribute a different meaning to the same VE at different times. For instance, in a study conducted by Mühlberger, Sperber, Wieser, and Pauli (2008), 34 participants with arachnophobia completed a behavioral avoidance test in VR before and after eight exposure trials and after each trial. Participants completed questionnaires on their fear of spiders, their beliefs about spiders, trait anxiety, their subjective distress levels, and bodily symptoms experienced during the behavioral avoidance test and the exposure trials. The authors also measured participants' heart rate (using an electrocardiogram [ECG]) and skin conductance levels. The results revealed that participants' fear of spiders did not diminish, and their heart rate and skin conductance levels remained elevated following the exposure trials. However, participants approached the spider closer after the exposure trials than before the trials. Participants' negative beliefs toward spiders also diminished after the exposure trials. The decrease in negative beliefs toward spiders could have enabled participants to approach the spider closer after the exposure trials. Even though the VE remained the same, participants' behavior changed because the spider did not have the same meaning before and after the exposure trials. These results are concordant with those of Côté and Bouchard (2009) and Tardif, Therrien, and Bouchard (2019) who found that a reduction in dysfunctional beliefs after immersions in VR decreased participants' fear of spiders. Participants also approached a live tarantula closer than they did pre-immersion.

2.3.4.4 Implicit and Explicit Behavior. Finally, VR is interactive (Steuer, 1992): a user's implicit and explicit behavior will further influence how the VE responds and which virtual and/or somatosensory stimuli (input) will be received and integrated by the brain (information processing), which will lead to subjective experience. For instance, if the users' task is to pick up a virtual box, they will physically move the controllers to move their virtual hands to pick it up. The VE will update their virtual hands' locations according to their physical hand movements. The updated locations of their virtual hands will indicate whether they have successfully picked up the box or whether they need to try again. Given that visual and proprioceptive information (input) are necessary to complete this task, they will be sent back into the information processing loop and integrated. In short, the implicit and explicit behavior feedback the input, information processing, and subjective experience loop (see the model in Figure 1).

3 Future Research

Testing the model of presence proposed in Figure 1 could be done by targeting the role of implicit multisensory information on subjective presence. Multisensory integration and visual realism could be experimentally manipulated by adding slight non-explicit delays between stimuli (i.e., disrupting multisensory integration) and contrasting this effect on presence to manipulations of levels of visual realism (e.g., number of polygons, lightmaps, textures). If the model holds, it is expected that slight delays in multisensory integration will be detrimental to the believability of the VE, and thus to presence, and even more than explicit reduced visual realism. The impact of the delays should also be objectively measurable by objective behaviors. Moreover, the experimental manipulation should impact behavioral measures of presence. When considering implicit information processing and behaviors, it would be interesting to examine the relationship between presence (plausibility and place illusions), visual realism, and multisensory integration in the context of fear. Many VEs used in VR are relevant for the treatment of anxiety disorders and involve fear (Wiederhold & Bouchard, 2014), which would provide a specific context to apply the model. But most importantly, fear influences attention and information processing, with a focus on threat and safety cues, and implicitly mobilizes action toward seeking safety. In the context of fear, it may be easier to control for implicit and explicit information processing and observe behavior that informs researchers on presence.

Additional future research could study the impact of expectations on presence since it seems that previous experience can have an impact on the brain's expectations. The appearance of virtual characters and/or objects could be experimentally manipulated. If their appearance does not have an effect on the believability of the VE (i.e., they resemble and behave like people and objects found in the physical environment or from a previous immersion), it is likely that users will still implicitly react to the characters and/or the objects as if they were "real." If their appearance has an effect on the believability of the VE (e.g., the human virtual characters have six legs and there is no logical explanation for why this is the case), users' behavior in the VE will likely not resemble their behavior in the physical environment or from a previous immersion where the virtual character had two legs.

In addition, it could be interesting to study the plausibility and place illusions separately since they appear to be distinct concepts (i.e., feeling that the virtual scenario is actually occurring vs. feeling of "being there" in the VE). It is possible that some factors have a larger influence on the plausibility illusion while others have a larger influence on the place illusion. Perhaps perceived realism has a larger effect on the plausibility illusion than on the place illusion since it contributes to the believability of the VE. Users could still feel as if they "are there" in the VE but feel like the reduced perceived realism is negatively affecting their feeling that virtual events are actually occurring.

4 Conclusion

Sensory and emotional stimuli are integrated in a multisensory manner to create a coherent representation of the world (Chalmers et al., 2009; Stein et al., 2009; Stein et al., 2014; Welch & Warren, 1980). Multisensory conflicts can lead to various perceptual illusions (e.g., the ventriloquism effect, body illusions). Two important multisensory integration principles have emerged from research: (1) the temporal principle, and (2) the spatial principle.

The brain seems to process sensory and emotional information in a similar way in VR. Although there are interesting neuroscientific models that explain how various perceptual illusions are induced in VR (i.e., Gonzalez-Franco & Lanier, 2017) and how embodiment is related to presence in VR (Riva et al., 2018; Riva et al., 2019), these models do not relate specifically to presence and multisensory integration. This is why a new model is proposed using elements of the models put forward by Lombard and Ditton (1997), Gonzalez-Franco and Lanier (2017), Riva et al. (2018), and Riva et al. (2019).

Future research could experimentally manipulate expectations (e.g., added delays in the VE, the appearance of virtual characters and objects) and further explore the mechanisms of the plausibility and place illusions and different factors that impact these illusions. This research would help us to better understand the contribution of multisensory integration to presence.

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Chapitre 3 : Les cybermalaises

Ce chapitre aborde les cybermalaises, un autre facteur important en RV. Les cybermalaises sont des effets négatifs indésirables que les utilisateurs peuvent ressentir pendant ou après une immersion en RV (p. ex., mal de tête, nausée, vertige). Le chapitre introduit en premier deux théories sur les cybermalaises et des facteurs pouvant avoir un effet sur ces derniers. Ensuite, le chapitre examine la relation entre les cybermalaises et la présence, notamment la manière dont les cybermalaises s'intègrent dans le modèle conceptuel de la présence présenté dans le Chapitre 2, lequel n'incluait pas les cybermalaises au moment de la publication. Finalement, la relation entre les cybermalaises et l'anxiété, ainsi que des mesures pour évaluer les cybermalaises sont abordées. Noter que ce chapitre suit le Chapitre 2 (plutôt que le Chapitre 1) afin de refléter l'évolution du projet de thèse et d'introduire les cybermalaises de manière conceptuelle avant la présentation des deux études expérimentales. Plus précisément, les cybermalaises ne faisaient pas partie du projet de thèse initial, mais ils ont été intégrés par la suite, en raison des résultats obtenus à la suite de la première étude empirique (voir Chapitre 4) et de l'importance des cybermalaises dans l'expérience des utilisateurs en RV.

Bien que les casques de RV se sont améliorés au cours des dernières années, les cybermalaises demeurent un problème important pour les applications dans plusieurs domaines et ont un impact négatif sur l'expérience de l'utilisateur (Yildirim, 2020). Il existe deux principales théories sur les cybermalaises : (1) la théorie du conflit sensoriel (*Sensory Conflict Theory*, Reason & Brand, 1975) et (2) la théorie de l'instabilité posturale (*Postural Instability Theory*, Riccio & Stoffregen, 1991). Selon la théorie du conflit sensoriel proposé par Reason et Brand (1975), les cybermalaises sont induits par un décalage entre les informations visuelles et vestibulaires (c.-à-d., la perspective de l'utilisateur se met à jour lorsqu'il se déplace dans l'environnement virtuel, mais son corps ne se déplace pas physiquement, ce qui peut entraîner un inconfort chez l'utilisateur). La vection réfère à cette perception illusoire du mouvement (Dichgans & Brandt, 1978 ; Palmisano et al., 2015). Par exemple, lorsqu'un utilisateur conduit dans un simulateur de conduite ou utilise des manettes pour se déplacer dans l'environnement virtuel, il voit le paysage changer, mais il reste physiquement au même endroit (informations visuelles et vestibulaires ne concordent pas). En revanche, dans l'environnement physique, lorsqu'un individu conduit un véhicule ou se déplace à pied, le paysage change et l'individu se déplace physiquement (informations visuelles et vestibulaires concordent).

Dans la littérature, la théorie de l'empoisonnement (*Poison Theory*, Treisman, 1977) est parfois regroupée avec la théorie du conflit sensoriel, car elle postule également que les symptômes des cybermalaises proviennent du conflit sensoriel entre l'information visuelle et vestibulaire. Toutefois, la théorie de l'empoisonnement introduit l'hypothèse que le corps a une réponse adaptative semblable à l'ingestion d'un poison lorsqu'il y a un conflit, ce qui favoriserait les nausées et les vomissements. Cette théorie ne sera pas abordée en profondeur dans la thèse, car elle n'est pas couramment utilisée dans l'étude des cybermalaises.

Une deuxième théorie utilisée pour expliquer les cybermalaises est la théorie d'instabilité posturale (Riccio & Stoffregen, 1991 ; Smart et al., 2002 ; Stoffregen, 2011 ; Stoffregen & Smart, 1998). La théorie initiale (Riccio & Stoffregen, 1991) a mis de l'avant l'hypothèse que l'instabilité posturale devrait précéder l'apparition des symptômes du mal des transports. En d'autres termes, la stabilité posturale des participants avant l'exposition à des stimuli potentiellement nauséogènes devrait différer entre les participants qui ressentent ultérieurement le mal des transports et ceux qui n'en ressentent pas. La théorie a été étendue aux cybermalaises en RV (p. ex., Bailey et al., 2022) en raison des similarités entre le mal des transports et les cybermalaises. Il est important de noter que la théorie ne définit pas l'instabilité posturale comme une simple augmentation du mouvement du corps. La stabilité ou l'instabilité réfère plutôt à la capacité de l'individu à atteindre ses objectifs posturaux (Stoffregen et al., 2008). Ainsi, si l'objectif postural de l'individu est de demeurer immobile et qu'il ne peut pas maintenir cette immobilité, il pourrait s'agir d'instabilité posturale. À l'inverse, certains objectifs posturaux peuvent nécessiter davantage de mouvement sans que cela signifie une instabilité posturale. Autrement dit, le contexte et la tâche sont importants pour interpréter les résultats.

Plusieurs études ont été menées pour évaluer la théorie de l'instabilité posturale à l'aide de simulateurs dans l'environnement physique et en RV. Les résultats de ces études ont montré que l'instabilité posturale précédait en effet l'apparition des symptômes du mal des transports (p. ex., Bonnet et al., 2006 ; Smart et al., 2002 ; Stoffregen & Smart, 1998 ; Stoffregan et al., 2000 ; Stoffregan et al., 2008 ; Villard et al., 2008). L'activité posturale des participants ayant éprouvé le mal des transports était également, avant l'apparition des symptômes, significativement différente de celle des participants n'ayant pas éprouvé le mal des transports. En revanche, une étude (Akiduki et al., 2003) a observé que l'instabilité posturale des participants était seulement significativement différente après les immersions, ce qui suggère que le mal des transports pourrait mener à l'instabilité posturale. Bien que de nombreuses études aient été menées dans le contexte du mal des transports, peu d'études ont examiné si ces résultats pouvaient être généralisés aux cybermalaises en RV. Dans une étude récente, Risi et Palmisano (2019a) ont révélé que l'activité posturale des participants ayant rapporté des cybermalaises en RV était significativement différente avant les immersions de celle des participants n'ayant pas rapporté de cybermalaises. Ce résultat soutient la théorie de l'instabilité posturale dans le cadre de la RV.

Toutefois, la relation entre la stabilité posturale et les cybermalaises mérite d'être explorée plus en profondeur.

Divers facteurs peuvent contribuer aux cybermalaises, notamment liés aux différences individuelles (Jasper et al., 2023), au logiciel ou à la conception de l'environnement virtuel (Quan et al., 2024) et à l'équipement utilisé (Stanney et al., 2020). Plusieurs facteurs individuels peuvent contribuer aux cybermalaises. Par exemple, des études antérieures ont trouvé une relation entre les cybermalaises et l'âge (Garrido et al., 2022 ; Keshavarz et al., 2018 ; Knight & Arns, 2006), le sexe (Jasper et al., 2020 ; Munafo et al., 2017), les antécédents de mal des transports (Jasper et al., 2023 ; Mazloumi Gavgani et al, 2018 ; Rebenitsch & Owen, 2014) et l'expérience antérieure des jeux vidéo (Hasibuan et al., 2025 ; Jasper et al., 2020 ; Pöhlmann et al., 2024 ; Rebenitsch & Owen, 2014 ; Weech et al., 2020) ou de la RV (Garrido et al., 2022 ; Rebenitsch & Owen, 2021). Toutefois, d'autres études n'ont pas trouvé de relation entre les cybermalaises et l'âge (p. ex., Jasper et al., 2023), le sexe (p. ex., Jasper et al., 2023 ; Melo et al., 2021) ou l'utilisation antérieure de la RV (p. ex., Jasper et al., 2023).

Pour ce qui est du logiciel ou de la conception des environnements virtuels, la méthode de déplacements (Clifton & Palmisano, 2020 ; Kim et al., 2023), la durée des immersions en RV (Risi & Palmisano, 2019b) et le niveau de charge de travail (*workload*, Jasper et al., 2023) peuvent avoir un impact sur les cybermalaises. De plus, les mouvements intenses (p. ex., accélération rapide) ou les grandes rotations (p. ex., manèges) peuvent induire des cybermalaises chez les utilisateurs, car ces types de mouvement augmentent le conflit entre les informations visuelles et vestibulaires (Quan et al., 2024). D'autre part, les environnements virtuels contenant des informations visuelles complexes, telles que des textures complexes qui changent rapidement, peuvent également contribuer aux cybermalaises, car la complexité visuelle surcharge les capacités de traitement visuel de l'utilisateur (Quan et al., 2024). Cependant, Sanaei et al. (2024) ont trouvé qu'une scène avec une complexité visuelle plus élevée n'a pas mené à des cybermalaises plus sévères qu'une scène moins complexe. Ces résultats mitigés suggèrent que les cybermalaises sont un phénomène complexe et peuvent varier en fonction de l'individu, de la tâche, du logiciel et de l'équipement.

Des facteurs liés à l'équipement peuvent entraîner ou aggraver les cybermalaises, tels qu'un champ de vision plus large (Teixeira & Palmisano, 2021), la latence (Palmisano et al., 2023) et le mauvais alignement de la distance interpupillaire (Stanney et al., 2020). Pour un aperçu détaillé des facteurs contribuant aux cybermalaises, voir les recensions systématiques par Biswas et al. (2024), Caserman et al. (2021), Pereira et al. (2024) et Saredakis et al. (2020), ainsi que les recensions des écrits par Chang et al. (2020) et Descheneaux et al. (2020).

La relation entre les cybermalaises et la présence est complexe. Quoique des études aient montré une corrélation positive entre les deux variables qui variait entre $r = 0.44$ et $r = 0.68$ (p. ex., Lin et al., 2002 ; Liu & Uang, 2011), d'autres ont trouvé une corrélation négative qui variait entre $r = -0.22$ et $r = -0.60$ (p. ex., Nichols et al., 2000 ; Weech et al., 2020 ; Witmer et al., 1996 ; Witmer & Singer, 1998) ou non significative (p. ex., Ling et al., 2012 ; Kooijman et al., 2022 ; Servotte et al., 2020). Dans une étude, Sepich et al. (2022) ont divisé les participants en trois groupes, chacun effectuant une tâche avec un niveau de charge de travail différent. Les résultats ont révélé une corrélation non significative entre les cybermalaises et la présence dans deux groupes et une corrélation négative significative dans le troisième, suggérant que la relation entre ces variables pourrait changer selon la tâche. Pour une discussion détaillée de la relation entre les cybermalaises et la présence, voir la recension des écrits par Weech et al. (2019).

Plus récemment, Quan et al. (2024) ont proposé que la relation entre les cybermalaises et la présence change en fonction du niveau de cybermalaises ressenti par les participants. Plus précisément, les résultats de leur étude ont révélé une corrélation positive entre les cybermalaises et la présence lorsque les cybermalaises étaient moins sévères, et une corrélation négative lorsque les cybermalaises étaient plus sévères. Lorsqu'un individu éprouve des cybermalaises sévères, il est probable qu'il prête attention à ses symptômes physiques plutôt qu'à l'environnement virtuel et que ces symptômes interfèrent avec l'intégration multisensorielle. En d'autres termes, il est probablement plus difficile pour l'individu de se sentir « là » dans l'environnement virtuel (présence diminue) s'il se concentre sur les symptômes qu'il ressent dans l'environnement physique (p. ex., nausées sévères, vertiges). En revanche, un individu qui ne ressent aucun (ou très peu) de cybermalaises peut ignorer ses symptômes et se concentrer sur l'environnement virtuel.

De nombreux facteurs qui influencent les cybermalaises peuvent également affecter la présence. Certains facteurs peuvent avoir un effet négatif sur les deux variables. Par exemple, un conflit visuo-vestibulaire tend à diminuer la présence et augmenter les cybermalaises (Kim, Luu, & Palmisano, 2020). D'autres facteurs peuvent avoir un impact positif sur une variable et négatif sur l'autre variable. Par exemple, un champ de vision plus large peut améliorer la présence (Sanchez-Vives & Slater, 2005) en rendant l'environnement virtuel plus semblable à l'environnement physique. Néanmoins, cela peut également exacerber les cybermalaises en augmentant le flux optique (Seay et al., 2002). La perspective à la troisième personne (perspective exocentrique), où les utilisateurs observent l'environnement virtuel sans pouvoir interagir avec celui-ci, peut également réduire la présence (Medeiros et al., 2018) et mener à des cybermalaises (Nam et al., 2022). Par conséquent, la conception d'environnements virtuels efficaces nécessite un équilibre entre les éléments qui peuvent avoir des effets à la fois positifs et négatifs sur l'expérience de l'utilisateur.

Les études ci-dessus suggèrent que les cybermalaises et la présence sont reliés, ce qui permet d'expliquer comment les cybermalaises pourraient être intégrés au modèle conceptuel sur la présence (Chapitre 2). Weech et al. (2019, 2020) ont proposé que les différences individuelles dans le traitement des conflits multisensoriels puissent contribuer à la relation négative entre les cybermalaises et la présence. Plus précisément, les auteurs ont supposé que les individus sensibles aux conflits multisensoriels pourraient avoir tendance à ressentir des cybermalaises plus sévères et une présence plus faible. Dans une étude, Kim, Luu et Palmisano (2020) ont exposé des participants à différents niveaux de conflit sensoriel en RV. Le conflit a été créé en ajoutant un décalage temporel entre les stimuli visuels et vestibulaires. Les résultats ont révélé que le conflit sensoriel a diminué la présence et aggravé les cybermalaises.

Champury et Shahnewaz Ferdous (2025) ont mené une étude semblable où les participants étaient exposés à des montagnes russes virtuelles avec différents niveaux de fidélité sensorielle (vidéo, sons, sensation de vent). Plus précisément, les participants ont été divisés en deux groupes et ont été exposés aux stimuli sensoriels dans l'un des deux ordres suivants :
(1) vidéo seulement, vidéo + audio et vidéo + audio + ventilateurs (*Increasing group*) ou
(2) vidéo + audio + ventilateurs, vidéo + audio et vidéo seulement (*Decreasing group*). Les résultats ont indiqué que l'ajout de stimuli sensoriels a eu un effet significatif sur certaines dimensions de la présence (réalisme perçu et perception de la vitesse) et les cybermalaises (auto-rapportés et rythme cardiaque). Spécifiquement, le réalisme perçu et la perception de la vitesse étaient plus élevés dans les conditions vidéo + audio + ventilateurs et vidéo + audio que dans la condition vidéo seulement. De plus, les cybermalaises (auto-rapportés et rythme cardiaque)

étaient moins sévères dans la condition vidéo + audio + ventilateurs que dans les conditions vidéo + audio et vidéo seulement. Ce résultat suggère que ce n'est pas seulement l'ajout de stimuli qui influence les cybermalaises, mais également le type et la qualité des stimuli. Il est important de noter que les auteurs ont utilisé un questionnaire personnalisé pour mesurer la présence. Ce dernier ne contenait pas de question sur le sentiment « d'être là » dans l'environnement virtuel. Il serait utile dans des études futures d'utiliser un questionnaire de la présence validé. Bref, les processus d'intégration multisensorielle semblent contribuer à la fois aux cybermalaises et à la présence. Ces facteurs communs suggèrent que les cybermalaises pourraient être incorporés dans le modèle conceptuel de la présence (Chapitre 2), qui propose que les mécanismes d'intégration multisensorielle jouent un rôle important pour induire la présence.

Des études antérieures ont révélé une relation entre les cybermalaises et l'anxiété en RV (p. ex., Bouchard et al., 2007 ; Bouchard et al., 2021). Dans une étude, Howard et Van Zandt (2021) ont révélé une corrélation positive entre l'anxiété et les cybermalaises en RV, mais seulement lorsque les participants étaient exposés à un objet phobogène, ce qui suggère que l'anxiété peut amplifier les cybermalaises. Dans sa thèse, Woolverton (2024) s'est inspiré de l'étude d'Howard et Van Zandt (2021) pour développer son modèle conceptuel. Dans l'étude expérimentale de Woolverton (2024), 65 étudiants universitaires ont écouté deux vidéos immersifs à 360° sur YouTube dans un ordre aléatoire : (1) une vidéo avec une faible intensité de mouvement et (2) une vidéo avec une intensité de mouvement élevée. Les participants ont rempli plusieurs questionnaires avant et après les immersions, y compris une version modifiée du *Cybersickness Questionnaire* (Stone III, 2017) et l'échelle d'anxiété situationnelle tirée de l'Inventaire d'anxiété état-trait (Spielberger et al., 1983). Avant, pendant et après les immersions, la stabilité posturale (à l'aide d'une *Wii Balance Board* par Nintendo) et le rythme cardiaque (à l'aide de l'équipement BIOPAC MP36) des participants ont été enregistrés. Les résultats ont révélé que les participants avec une anxiété situationnelle modérée ou élevée ont rapporté des cybermalaises pré- et post-immersion plus sévères que ceux avec une anxiété situationnelle faible. D'autre part, la stabilité posturale était pire pendant les immersions qu'avant les immersions, peu importe le niveau d'anxiété situationnelle. Bref, ces résultats suggèrent une relation entre les cybermalaises et l'anxiété. Toutefois, il serait utile d'explorer la relation entre ces variables dans un environnement virtuel interactif et de manipuler l'anxiété directement (p. ex., en exposant les participants à un objet ou une situation phobogène).

Il existe plusieurs méthodes pour mesurer les cybermalaises, dont les mesures auto-rapportées, les mesures physiologiques et les mesures comportementales (Davis et al., 2014 ; Rebenitsch & Owen, 2016 ; Tian et al., 2022). Un des questionnaires les plus souvent utilisés pour évaluer les cybermalaises est le *Simulator Sickness Questionnaire (SSQ)* par Kennedy et al. (1993). D'autres questionnaires souvent utilisés en recherche sont le *Motion Sickness Susceptibility Questionnaire (MSSQ)* par Golding (1998, 2006), le *Virtual Reality Symptoms Questionnaire* par Ames et al. (2005), le *Fast Motion Sickness Scale (FMS)* par Keshavarz & Hecht (2011), le *Cybersickness Questionnaire (CQ)* par Stone III (2017) et le *Virtual Reality Sickness Questionnaire (VRSQ)* par Kim, Park, et al. (2018). Le prochain paragraphe aborde le *Simulator Sickness Questionnaire (SSQ)* plus en détail, car il a été utilisé dans les deux études expérimentales du projet de thèse.

Le SSQ, développé par Kennedy et al. (1993), évalue les symptômes liés aux cybermalaises. Le questionnaire est souvent administré avant la première immersion en RV et après chacune des immersions. La version originale du questionnaire comprend trois sous-échelles : (1) Nausée (*Nausea*), (2) Oculomoteur (*Oculomotor*) et (3) Désorientation (*Disorientation*). Un score est calculé pour chacune des sous-échelles, puis un score total en pondérant les sous-échelles (voir Kennedy et al., 1993). Le SSQ a été validé et est couramment utilisé dans la recherche en RV, ce qui permet de comparer les résultats entre les études. À la suite d'une analyse en composantes principales, Bouchard et al. (2021) ont proposé une méthode alternative de diviser les sous-échelles et de calculer les scores. Spécifiquement, ils ont séparé le questionnaire en deux sous-échelles : (1) Nausée et (2) Oculomoteur. Pour calculer les scores des sous-échelles et le score total, il faut d'abord additionner les items propres à chaque sous-échelle (*SSQ-Nausea-Raw* et *SSQ-Oculomotor-Raw*), puis additionner les scores des deux sous-échelles pour obtenir le score total (*SSQ-Total-Raw*). Les auteurs suggèrent également de calculer des scores corrigés, car ils ont trouvé une corrélation entre certains items du SSQ et l'anxiété. Plus précisément, les calculs sont identiques à ceux ci-dessus, mais ils excluent les items liés à l'anxiété (*SSQ-Nausea-Anx*, *SSQ-Oculomotor-Anx* et *SSQ-Total-Anx*). Noter que les deux études expérimentales du projet de thèse ont utilisé la méthode proposée par Bouchard et al. (2021) pour calculer les scores des sous-échelles et le score total du SSQ.

Des études ont proposé d'utiliser des mesures alternatives pour évaluer les cybermalaises (p. ex., Weissker, sous presse). Par ailleurs, des études ont utilisé des mesures physiologiques, telles que le rythme cardiaque et la conductivité électrique de la peau (p. ex., Kim et al., 2005 ; Magaki & Vallance, 2019 ; Setiowati et al., 2020), ou des mesures de stabilité posturale (p. ex., Chardonnet et al., 2017 ; Chia & Palmisano, 2024 ; Dennison & D'Zmura, 2017 ; Häkkinen et al., 2002 ; Risi & Palmisano, 2019b ; Teixeira et al., 2025 ; Wang et al., 2024). Plusieurs études qui mesurent la stabilité posturale utilisent des plateformes de force[2] et analysent les paramètres

[2] Les plateformes de forces sont des appareils qui ressemblent à un pèse-personne électronique.

de centre de pression (*centre of pressure [COP] parameters*), tels que la surface de l'ellipse, le déplacement total, la vitesse moyenne de déplacement, etc. (voir Paillard & Noé, 2015 pour une liste de paramètres).

Quelques études ont examiné la relation entre les cybermalaises et la stabilité posturale chez différents groupes de participants. Par exemple, Arcioni et al. (2019) ont trouvé que les participants ayant vécu des cybermalaises pendant les immersions en RV avaient une surface d'oscillation (*sway area*) significativement plus grande pré-immersion que ceux n'ayant pas rapporté de cybermalaises. Cependant, les groupes n'ont pas présenté de différences significatives pour les quatre autres paramètres de centre de pression analysés. D'autre part, seul un des paramètres était significativement corrélé avec les cybermalaises auto-rapportés. Dans une autre étude, Litleskare (2021) ont montré que la stabilité posturale post-immersion des participants « bien » et « malade » n'était pas significativement différente. Les résultats ont également révélé d'importantes variations individuelles dans la stabilité posturale. De plus, les résultats étaient mitigés quant aux corrélations entre les cybermalaises et les changements dans la stabilité posturale. Bref, ces résultats mitigés suggèrent que la relation entre les cybermalaises et la stabilité posturale est complexe (Litleskare, 2021) et que de la recherche plus poussée est nécessaire pour déterminer si la stabilité posturale est une mesure et un prédicteur adéquats des cybermalaises. D'autre part, la direction des effets de cette relation n'est pas claire non plus (Gallagher & Ferrè, 2018). Plus précisément, l'instabilité posturale pourrait mener aux cybermalaises ou vice versa. Autrement dit, il demeure incertain si l'instabilité posturale est une cause ou une conséquence des cybermalaises.

Des études antérieures ont montré que l'instabilité posturale peut augmenter dans des situations où il y a un conflit visuo-vestibulaire (Redfern et al., 2001), telles que les situations en hauteur (Bzduskova et al., 2021 ; Chander et al., 2021 ; Hackney et al., 2015). Toutefois, il peut être difficile de distinguer l'anxiété et les cybermalaises lorsqu'on tient compte seulement des symptômes physiques ou des résultats d'un test d'équilibre, car les deux conditions ont des symptômes semblables (p. ex., transpiration, nausées, étourdissements) et peuvent mener à l'instabilité posturale. En effet, plusieurs études ont trouvé que les symptômes d'anxiété et des cybermalaises peuvent être confondus (p. ex., Bouchard et al., 2007 ; Bouchard et al., 2009 ; Bouchard et al., 2021 ; Ling et al., 2011 ; Quintana et al., 2014). L'utilisation d'une combinaison de mesures permettrait de mieux distinguer ces deux variables.

Des études ont rapporté une relation entre l'anxiété et la stabilité posturale (Ohno et al., 2004 ; Wada et al., 2001), par exemple, chez les individus avec une phobie des hauteurs (Boffino et al., 2009 ; Coelho & Balaban, 2015 ; Coelho et al., 2017). Cependant, peu d'études semblent avoir exploré la relation entre l'anxiété et la stabilité posturale en RV spécifiquement. Ces études ont observé des différences dans la stabilité posturale des participants lorsqu'ils étaient exposés à un environnement virtuel en hauteur (p. ex., Bzduskova et al., 2021 ; Chander et al., 2021 ; Cleworth et al., 2012 ; Simeonov et al., 2005 ; Simeonov et al., 2011 ; Wuehr et al., 2019). Dans une étude (Bzduskova et al., 2021), les participants avec une peur des hauteurs plus élevée avaient une stabilité posturale réduite par rapport aux participants avec une peur des hauteurs moins élevée. Une autre étude (Wang et al., 2024) a révélé des différences individuelles liées au style perceptivo-moteur pendant la marche en hauteur en RV (p. ex., différences dans la posture, la démarche).[3]

Dans les situations impliquant des hauteurs, l'information visuelle pour maintenir l'équilibre est moins fiable, car la hauteur élimine les repères visuels qui peuvent être utilisés

[3] D'autres études ont évalué la stabilité posturale chez les personnes âgées ou d'autres populations vulnérables en RV afin de prévenir les chutes, mais elles ne sont pas abordées, car elles sont au-delà du sujet de la thèse.

pour le contrôle de la posture. Les individus doivent donc se fier à l'information proprioceptive (Bzduskova et al., 2021). En d'autres termes, lorsque les individus sont exposés à des hauteurs, l'instabilité posturale augmenterait chez ceux ayant une dominance visuelle par rapport à ceux ayant une dominance proprioceptive (c.-à-d., la conscience de son corps dans l'espace, Coelho & Balaban, 2015). L'évaluation de la stabilité posturale (p. ex., à l'aide de plateformes de force) permettrait de déterminer si un individu a une dominance visuelle ou proprioceptive. Lorsque les stimuli visuels sont éliminés (en demandant à l'individu de fermer les yeux), les individus ayant une dominance visuelle sont plus susceptibles de montrer des signes d'instabilité posturale que ceux ayant une dominance proprioceptive.

En résumé, quoique des études antérieures aient exposé des participants à un environnement virtuel anxiogène et aient mesuré la présence et les cybermalaises (p. ex., Gromer et al., 2018 ; Robillard et al., 2003), elles n'ont pas directement examiné la relation entre les cybermalaises, la présence et l'anxiété. La relation entre ces variables et la stabilité posturale demeure également peu étudiée.

Chapitre 4 : Exploring Self-Reported and Behavioral Presence in a Context of Anxiety Using a Virtual Sliding Door Paradigm

(Article 2)

Exploring self-reported and behavioral presence in a context of anxiety using a virtual sliding door paradigm

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Acknowledgements

The authors wish to thank Marie-Christine, Paul, Maxence, Mathilde, and Simon for developing the virtual environments used in the study. The authors also thank the participants who took part in the study. Finally, the authors would like to thank Anne and Meghan for supporting data collection.

Funding

The following funding agencies provided financial support for the research infrastructure and development of the virtual environment: Canada Research Chairs (#210762, 231039) and Canada Foundation for Innovation (#11138).

Conflict of interest

SB is president and owner of Cliniques et Développement In Virtuo, a spin-off company from his university that distributes virtual environments. The terms and arrangements for this spin-off have been reviewed and approved by the Université du Québec en Outaouais in accordance with its Conflict of Interest policies. He also receives honoraria from conferences, workshops, and books. The remaining authors have no relevant financial or non-financial interests to disclose.

Data availability

The data that supports the findings of this study is available upon request addressed directly to the relevant Research Ethics Boards (comite.ethique@uqo.ca and ethique@uottawa.ca). The datasets are not publicly available due to privacy and ethical restrictions.

Highlights

- Presence measured through questionnaires and shoulder rotations in virtual reality.
- No significant correlation between self-reported and behavioral presence.
- Unexpected behaviors observed, such as compressing shoulders and using hands.
- Significant correlation between self-reported presence and cybersickness.

Abstract

Presence, or the feeling of "being there", is a central component of virtual reality. Presence is commonly evaluated using self-report measures, such as questionnaires. However, these measures often assess presence retrospectively rather than in real-time. The current study examined whether participants physically rotated their shoulders to pass through narrow virtual sliding doors – a behavioral measure of presence – in a context of anxiety. Twenty-five participants were immersed in three virtual environments: (1) Risk of falling condition (deep virtual pit), (2) Risk of falling + Fire condition (deep virtual pit and fire), and (3) Control condition (no experimental manipulation). All participants were exposed to the Control condition first, followed by the two remaining conditions in a randomized order. During the immersions, participants physically walked on a virtual wooden plank (with a matching counterpart in the laboratory). Participants completed several questionnaires before and after the immersions, such as the ITC-Sense of Presence Inventory, the State-Trait Anxiety Inventory, and the Simulator Sickness Questionnaire. The results showed that the amplitude of shoulder rotations to pass through the virtual doors did not significantly correlate with self-reported presence or anxiety. The correlation between self-reported presence and anxiety was not statistically significant. Participant feedback suggested that the virtual environment did not meet some participants' expectations, which may have affected their self-reported presence and anxiety levels. However, the results revealed unexpected behaviors (e.g., using hands, compressing shoulders) and a statistically significant correlation between self-reported presence and cybersickness, which will be further explored in further studies.

Keywords: Anxiety, Narrow aperture, Presence, Shoulder rotation, Virtual reality

1. Introduction

Virtual reality (VR) has become more widely adopted over the past decades with the release of more affordable VR headsets, such as the Meta Quest. VR applications span many fields, including psychotherapy (e.g., for treating anxiety disorders, Wiederhold & Bouchard, 2014), education (e.g., as a teaching and learning tool, Cooper et al., 2019), training (e.g., simulators for pilots, Romano & Brna, 2001 and surgeons, IJsselsteijn et al., 2000), and entertainment (e.g., for video games, Bowman & McMahan, 2007). One central component of VR is presence. Presence in VR has commonly been defined as the perceptual illusion of "being there" in the virtual environment (Heeter, 1992). Understanding the role of presence is important for VR applications that aim to recreate scenarios from the physical environment and evoke similar (or identical) emotional and behavioral responses, such as in training or psychotherapy.

According to Slater (2009, 2018) and Slater et al. (2010, 2022), two illusions contribute to users behaving realistically in VR: (1) place illusion and (2) plausibility illusion. Place illusion refers to the notion of being transported elsewhere associated with presence, as described above (i.e., the feeling of being in the virtual environment). Plausibility illusion refers to the feeling of realness of the virtual environment. These two illusions affect user behavior (Berthiaume et al., 2018): when users feel like the events in the virtual environment are actually occurring and like they are actually "there" in the virtual environment, they are more likely to behave realistically. For example, when individuals are exposed to heights in VR, and they feel like they are in the virtual environment (place illusion) and like the scenario is actually occurring (plausibility illusion), they will likely react to it as they would in the physical environment (e.g., report higher anxiety, walk more slowly). For many applications, such as training and psychotherapy, it is important that individuals behave realistically in VR, as it is expected that they will generalize their behavior from the physical environment to VR and vice versa (e.g., safety training for working at heights). Immersion is another important component of virtual environments. Immersion refers to the objective characteristics of the technology used to immerse users that can be quantified and objectively measured, such as a head-mounted display's resolution or refresh rate (Bowman & McMahan, 2007; Slater, 2009). Despite the characteristics of the technology remaining consistent throughout the VR immersions, a user's presence levels may vary (Bowman & McMahan, 2007).

Recent studies have examined the place and plausibility illusions separately in VR (e.g., Hofer et al., 2020; Skarbez et al., 2018; Skarbez et al., 2022; Slater et al., 2023), with a few studies investigating these illusions using an anxiety-inducing virtual environment (e.g., Brübach et al., 2025; Lin, 2017; Shin et al., 2024). However, it would be useful to explore this area of research further, since anxiety induction is an important application of VR (e.g., for training, VR-based exposure treatment for phobias).

Anxiety and presence

Many studies have exposed participants to virtual environments containing heights or deep virtual pits (e.g., Brübach et al., 2025; Meehan et al., 2002, 2003; Slater et al., 1995; Usoh et al., 1999), since heights represent a natural threat (Bzduskova et al., 2021), and fear of heights is common (Abelson & Curtis, 1989; Andreassi, 1995; Poulton & Menzies, 2002). Studies have shown that virtual heights are effective at eliciting self-reported, physiological, and behavioral anxiety (Boccignone et al. 2023; Gromer et al., 2019; Kisker et al., 2021; Peterson et al., 2018; Zhu et al., 2021), though one study found that participants' anxiety saturated at heights superior to 40 m (Wuehr et al., 2019). Virtual environments that simulate heights have been used across various research domains, including clinical applications (Wiederhold & Bouchard, 2014) and construction safety (Chander et al., 2021; Cordeiro et al., 2025; Habibnezhad et al., 2019; Simeonov et al., 2011). A better understanding of the relationship between presence and anxiety in virtual environments involving heights could help improve their effectiveness and ensure that user behavior is realistic. Previous studies have also shown that other types of threatening stimuli are effective at increasing physiological and reported arousal, such as virtual fire (McCall, et al., 2015; McCall et al., 2016).

Several previous studies have shown that when participants experienced higher anxiety in anxiety-inducing virtual environments, they also experienced higher presence (e.g., Alsina-Jurnet et al., 2011; Gromer et al., 2019; Kisker et al., 2021; Maymon et al., 2024; Robillard et al., 2003). For example, in one study, Bouchard et al. (2008) exposed 31 participants with snake phobia to an anxiety-inducing virtual environment and a non-anxiety-inducing virtual environment in a randomized order. The results from a verbal measure showed that participants' presence was higher when they were exposed to the anxiety-inducing virtual environment than when they were exposed to the non-anxiety-inducing virtual environment, which suggests that higher anxiety led to higher presence. More recent studies, such as Brübach et al. (2025), Gromer et al. (2019), Kisker et al. (2021), and Maymon et al. (2024) have found that higher self-reported presence led to higher self-reported anxiety in virtual environments simulating heights.

Although these studies showed that there exists a relationship between anxiety and presence, the direction (which variable precedes the other) and the shape (linear or non-linear, Bouchard et al., 2012) of the relationship remain unclear. In other words, higher presence could lead to higher anxiety or vice versa. Moreover, some studies indicated a negative correlation between presence and anxiety (e.g., Ling et al., 2012; Villani et al., 2012). Given these mixed results, it would be useful to further investigate the relationship between the two variables. For a literature review on the relationship between anxiety and presence, see the meta-analysis conducted by Ling et al. (2014).

Measuring presence

Various measures have been used to assess presence, such as self-report (e.g., questionnaires, verbal measures, interviews), physiological (e.g., heart rate, skin conductance, skin resistance, respiration rate, pupillometry, brain imaging; Athif et al., 2020; Insko, 2003; Meehan et al., 2005; Wiederhold et al., 2001), and behavioral measures (e.g., reflexes, sensorimotor control, performance; Mestre, 2015; Mestre & Fuchs, 2006). However, few studies have used a combination of measures, particularly physiological and behavioral, to evaluate presence (one exception being two recent studies by Maymon et al., 2024). To the authors' knowledge, there are currently few physiological or behavioral measures of presence that have been shown to be correlated with self-reported presence and replicated in other studies (e.g., heart rate; Higuera-Trujillo et al., 2017; Meehan et al., 2002; Wiederhold et al., 2001).

Despite the usefulness of self-report measures to evaluate the subjective experience of presence, they are often administered post-immersion, and thus, retrospectively assess presence (e.g., Bouchard et al., 2008; Gromer et al., 2019; Kisker et al., 2021). Users occasionally complete self-report measures during the immersions, but this can be distracting and may reduce or break presence (IJsselsteijn et al., 2000). Physiological reactions are considered more reliable and objective than self-report measures, as they are automatic and implicit (IJsselsteijn et al., 2000). However, further research is needed to evaluate whether physiological measures are valid measures of presence, as they may assess the emotional reaction of users to stimuli, or emotional arousal, rather than presence *per se* (Diemer et al., 2015).

To the authors' knowledge, few studies have used a combination of different measures to assess presence. For example, Bouchard et al. (2008) administered self-report measures only to evaluate presence (questionnaire and brief measure). In another study, Gromer et al. (2019) used self-report (questionnaires) and physiological measures (heart rate and skin conductance). However, the authors did not seem to perform correlational analyses between self-reported presence and physiological measures. Similarly, Kisker et al. (2021) employed self-report (questionnaires), physiological (heart rate), and behavioral measures (walking time). The results showed that total walking time was significantly positively correlated with general and spatial presence. The authors did not seem to calculate correlations between self-reported presence and heart rate.

Lastly, behavioral measures assume that if users feel present in the virtual environment, their reactions should closely resemble those in the physical environment (Mestre, 2015). For example, the virtual sliding doors paradigm developed by Lepecq et al. (2009) and Mestre et al. (2016) involves participants physically rotating their shoulders to pass through a narrow aperture. Participants who feel present should rotate their shoulders to pass through the aperture (despite the absence of physical doors) whereas those who do not feel present should not rotate their shoulders or collide with the doors. Furthermore, the authors hypothesized that participants with larger shoulders would show greater angles of shoulder rotation than participants with narrow shoulders. The virtual environment enabled natural walking, which can enhance presence compared to navigation using a joystick (Usoh et al., 1999). The authors found that the average aperture to shoulder critical ratio (i.e., the aperture to shoulder width ratio where each participant rotated their shoulders to pass through the doors) was 1.22 for participants with narrow shoulders and 1.29 for participants with wide shoulders. While both studies hypothesized that behavior in the virtual environment would be related to presence, neither assessed self-reported presence. The methodology of the current study was based on Lepecq et al. (2009) and Mestre et al. (2016).

One variable that could affect shoulder rotations is a postural threat. A previous study in the physical environment (Hackney et al., 2015) showed that the magnitude of shoulder rotations was smaller when crossing a narrow aperture in a condition at heights than in a condition on the ground, which suggests that heights can influence shoulder rotations. However, the study did not analyze self-report measures. In addition, it is unclear whether heights in VR would have a similar effect on shoulder rotations. Understanding the impact of heights on navigating narrow spaces in VR could have important implications for contexts such as construction safety, where work in elevated narrow spaces can occur.

In summary, few studies have used both behavioral and subjective measures to assess presence. Given the current state of knowledge, utilizing measures addressing observable and subjective responses should provide a more comprehensive understanding of presence.

Objectives and hypotheses

Pilot testing was conducted prior to the current study. The pilot testing aimed to fine-tune the timing of the procedures and the use of the software. The study design was based on Lepecq et al.'s (2009) and Mestre et al.'s (2016) virtual sliding doors paradigm, applied in a novel context of anxiety. The current study explored the relationship between anxiety and presence (self-reported and behavioral). Specifically, the study evaluated whether participants rotated their shoulders when anxiety was experimentally induced. The study put forward the following hypotheses:

1) Participants will rotate their shoulders to pass through the virtual doors when they feel present.
2) The amplitude, or angle (in degrees), of the shoulder rotation will correlate with the self-report measure of presence.
3) The behavioral measure of presence (i.e., shoulder rotation) will correlate significantly with the measure of anxiety.
4) Presence will be highest in the condition expected to induce higher anxiety.

2. Methods

The study was approved by the Research Ethics Boards of the Université du Québec en Outaouais (#2021-1359) and the University of Ottawa (#H-03-21-6772). All participants gave their written consent to take part in the study.

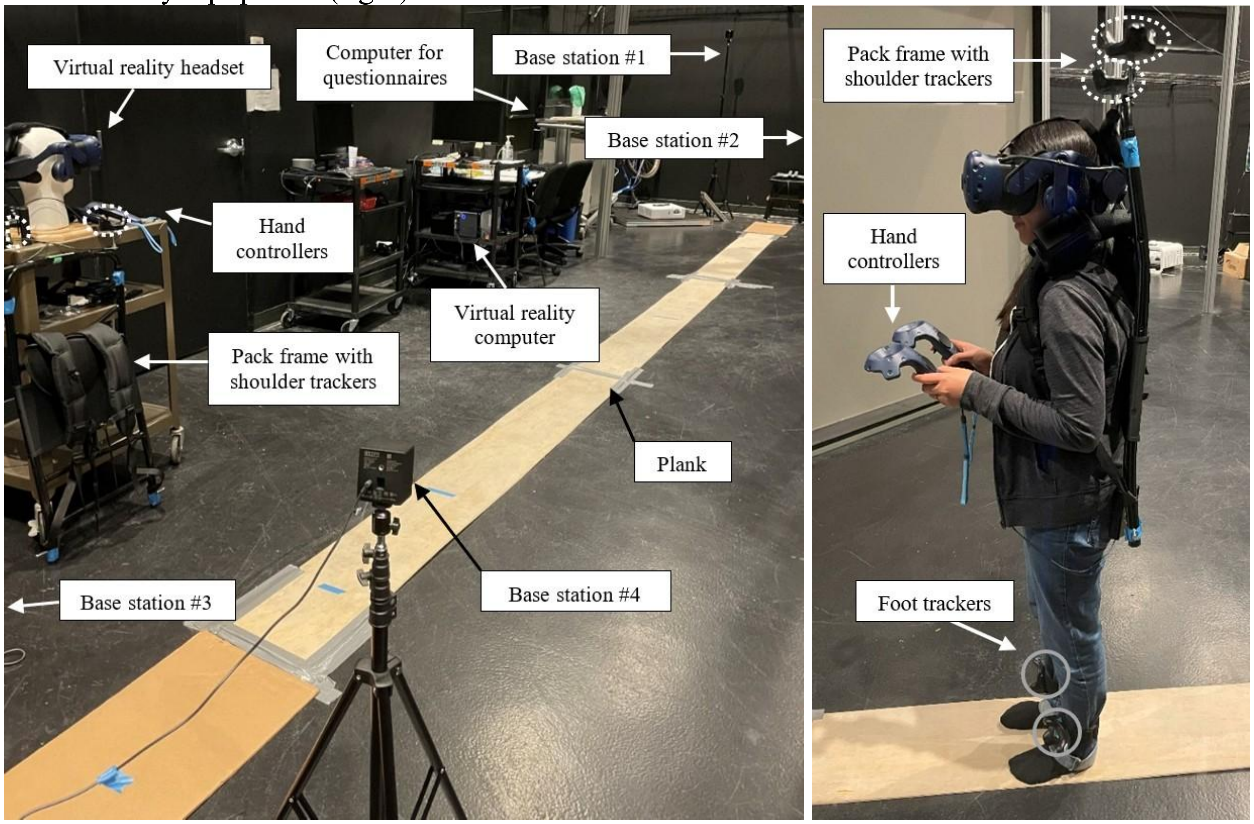
Participants

A convenience sample of 35 participants (16 women; 18 men; 1 unknown) were recruited at the University of Ottawa and the Université du Québec en Outaouais. Participants were excluded during recruitment if they met any of the following criteria: having a medical or psychological condition for which VR is not recommended (migraines; epilepsy; cardiac, vestibular, or important ocular conditions; frequent discomfort or motion sickness while travelling; psychotic disorder or schizophrenia; substance abuse) or having a phobia of fire or heights. These criteria did not lead to any exclusions. However, 11 participants were excluded during data collection for the following reasons: (1) poor stereoscopic vision (i.e., score greater than 70 seconds of arc at 16 inches, $n = 3$); and (2) technical issues ($n = 8$). The final sample included 24 participants (12 women; 12 men) for the analysis of shoulder data and 25 participants (12 women; 13 men) for the analysis of questionnaire data. The mean age of participants (n = 25) was 27.92 (SD = 10.33, range from 18 to 56).

VR equipment

The data collection took place at the Cyberpsychology Laboratory of the Université du Québec en Outaouais. Participants were immersed in the virtual environments via a VIVE Pro head-mounted display (dual AMOLED screen, screen size: 3.5" diagonal, field of view: 110°, resolution: 1440 x 1600 pixels per eye, refresh rate: 90 Hz). The headset's in-built headphones delivered spatialized sound, and participants used the VIVE hand controllers to move virtual hands. Two VIVE Trackers 2018 tracked participants' shoulders and two VIVE Trackers 2018 tracked their feet (https://www.vive.com/ca/support/wireless-tracker/). The trackers for tracking participants' shoulder movements were placed on a metal rod attached to a pack frame (i.e., a rigid metal frame; see Figure 1 for a photo of the experimental setup). The pack frame with the two shoulder trackers weighed 3.40 pounds (1.54 kilograms). The shoulder trackers were placed on the metal rod at a fixed position that was identical for all participants.

Figure 1 Photos of the experimental setup in the laboratory (left) and of a participant wearing the virtual reality equipment (right)



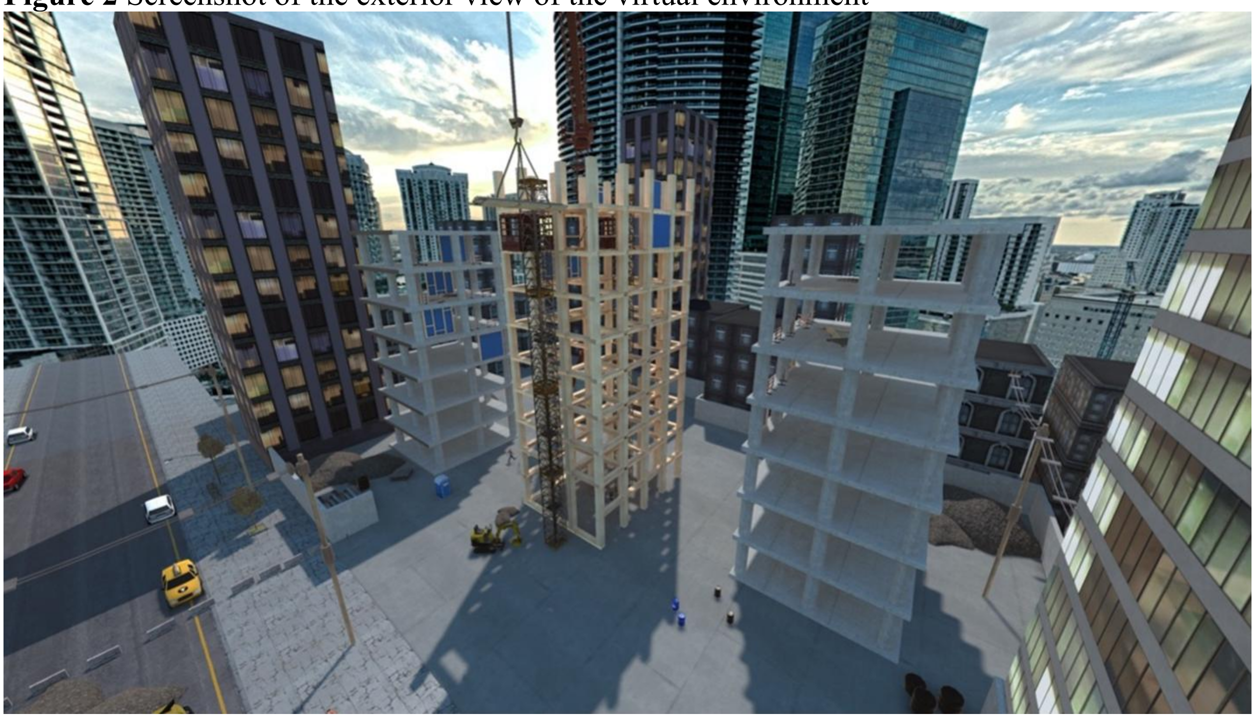
Note. Both photos: The shoulder trackers (on the pack frame) are circled in white (dotted line). Photo on the left: Base stations #2 and #3 are not visible in the photo. Photo on the right: The foot trackers (around the ankles) are circled in grey (solid line).

Four SteamVR Base Stations 2.0 (https://www.vive.com/us/accessory/base-station2/) tracked the movement of the VR headset and trackers. The headset was wirelessly connected to a desktop computer via a VIVE Wireless Adapter (https://www.vive.com/ca/accessory/wireless-adapter/) to enable natural walking during the immersions. The desktop computer ran on Windows 10 Pro (Intel® Core™ i7-4790 CPU @ 3.60GHz, 32 GB RAM, 64-bit operating system) with an NVIDIA GeForce RTX 2070 graphics card (version 3.27.0.112). The experimenter controlled the settings for the virtual environments on the desktop computer.

Virtual environments

The virtual environments were developed using the Unity 3D game engine version 2021.3.6f1 (Unity, 2021) and run via the SteamVR application developed by Valve Corporation (version 1.24.7; https://www.steamvr.com/en/). The virtual environments represented a construction site in a downtown area (see Figure 2) and were developed based on photographs of actual construction sites. The goal while developing the virtual environments was to maintain high fidelity. Due to practical and time constraints, it was not possible to reproduce all the details from the photographs; instead, the team focused on reproducing the elements that appeared in several of the photographs (e.g., crane, buildings under construction, piles of dirt or gravel).

Figure 2 Screenshot of the exterior view of the virtual environment



Note. The experimental trials took place in the brown elevator cage on the left of the central tower.

Practice environment

A practice environment (see Figure 3) familiarized participants with VR. Specifically, participants could practice navigating and interacting with the virtual environment using the hand controllers and experience presence for a first time before being exposed to experimental manipulations. This environment consisted of a 2-minute walk on a virtual wooden plank on the ground floor of a virtual skyscraper under construction. As such, the practice environment did not provide the impression of being at a height. The plank measured approximately 30 cm in width and 7 m in length and was used in all experimental conditions. These dimensions were selected to ensure that participants had enough space to complete the task. Participants' task was to press a virtual button at opposite ends of the plank (see Procedure for additional details). The button's appearance and position inside the elevators were identical in all virtual environments. Participants walked without shoes and in their socks on a physical plank of identical dimensions to provide haptic feedback and increase the realism of the scenario.

Figure 3 Screenshot of the virtual environment for the practice trial

Note. This virtual environment served to help familiarize participants with the VR equipment and the task to complete (i.e., press the buttons).

Main environment

All experimental conditions took place in the main virtual environment, on the eighth floor of the virtual skyscraper under construction (virtual height of 35 m from the virtual ground floor based on Wuehr et al., 2019). On the floor where participants were located, there were wooden beams and two elevators positioned at opposite ends. Each elevator door was 10 cm thick and could open and close to a narrower width. When they were fully open, they were 250 cm wide. When they partially closed to a narrower width, the aperture width was adjusted according to participants' physical shoulder width (i.e., the width of participants' virtual shoulders corresponded to the width of their physical shoulders, not the width of the pack frame). Specifically, the current study implemented an aperture to shoulder ratio of 0.82 (i.e., aperture width narrower than participants' shoulders) based on the results from Lepecq et al.'s (2009) and Mestre et al.'s (2016) studies. This ratio was selected to ensure that all participants physically rotated their shoulders. In other words, the aperture width was larger for participants with wider shoulders than for participants with narrower shoulders.

The virtual ceiling and floor were made of wood. "Caution tape" placed between the wooden beams guided participants towards the elevators, ensuring that they walked in a straight line and preventing them from exploring the virtual environment. The lower floors contained barriers, barrels, piles of wood, etc. Outside the building, animated trucks lifted materials, and a crane slowly rotated in the distance. These elements were included to increase the realism of the virtual environment. However, to avoid distracting the participants, the trucks remained in one location of the construction site, and the crane moved very slowly and far away from participants. Faint spatialized city and construction sound effects played in the background (e.g., truck engines, birds chirping, traffic, a siren in the distance). In all experimental conditions, participants walked on the same plank used in the Practice environment.

Control condition: In the virtual environment for this condition, a floor beneath the wooden plank hid the lower floors of the building (see Figure 4). In other words, there was no perceived risk of falling in this condition. In all experimental conditions, participants had virtual hands and feet, which matched the movements of their tracked physical hands and feet (see Figure 5).

Figure 4 Screenshot of the virtual environment for the Control condition

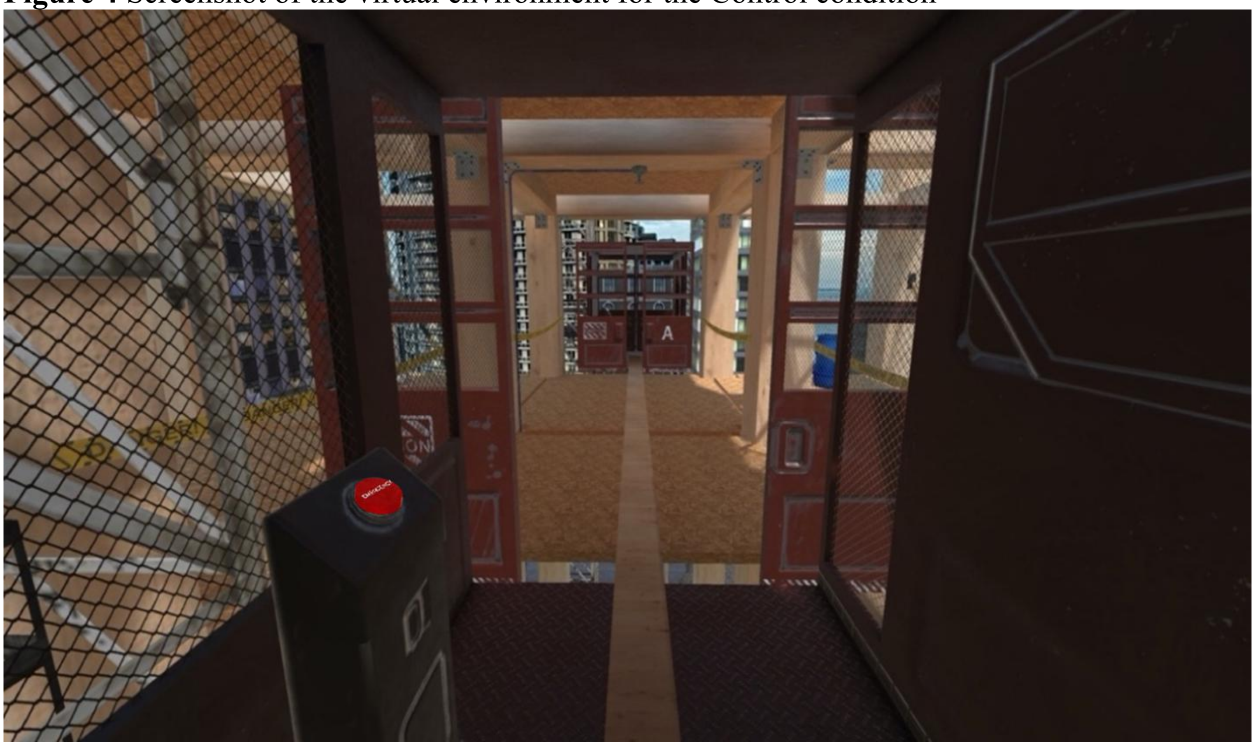
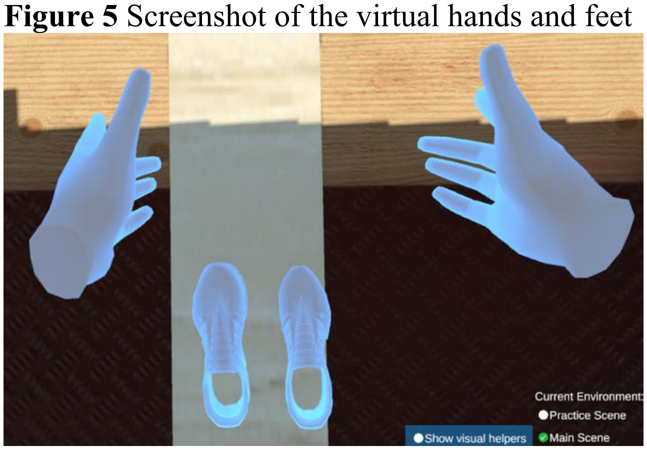
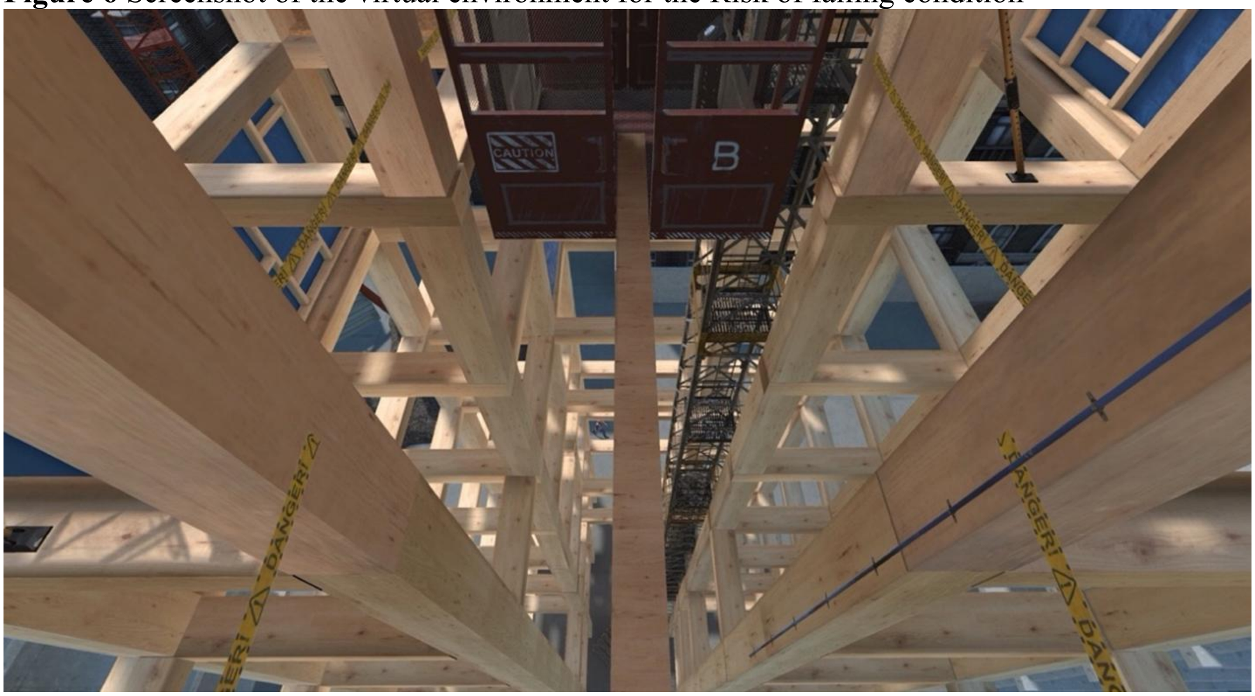


Figure 5 Screenshot of the virtual hands and feet



Risk of falling condition: The virtual environment for this condition (virtual pit; see Figure 6) was identical to the Control condition, except that the floor surrounding the virtual plank was removed to elicit anxiety. The relatively narrow width of the plank (30 cm) forced participants to look at their feet and see a deep pit, which the authors expected would increase their anxiety level. If participants looked down, they could see lower floors (including the ground floor) and the outdoor environment.

Figure 6 Screenshot of the virtual environment for the Risk of falling condition



Risk of falling + Fire condition: In this condition, the Risk of falling virtual environment was used, except that the wooden beams, plank, and ceiling caught fire as the participant moved forward (see Figure 7). The virtual environment also contained virtual smoke and a spatialized sound of crackling wood burning. The fire lit up in sections as the participant progressed forward in the direction of the virtual doors. This procedure was chosen to prevent them from freezing or turning back and returning to the elevator behind them. Fire was selected as an anxiety-inducing element, as it is a natural fear. This condition was expected to induce the highest level of anxiety.

Figure 7 Screenshot of the virtual environment for the Risk of falling + Fire condition as seen where participants were looking behind them

Measures

Several questionnaires and a behavioral measure were used to assess presence. The participants filled out questionnaires before and immediately following the immersions in VR. If they were francophone, they completed a French version of the questionnaires. These questionnaires were selected for their demonstrated reliability and validity.

The dependent variables were presence levels (as assessed by the aforementioned questionnaires and behavioral measure). The independent variable was the experimental condition (Control, Risk of falling, and Risk of falling + Fire). Anxiety levels were measured with a questionnaire as a manipulation check to validate the independent variable. All questionnaires were completed via LimeSurvey on a separate desktop computer. Additional details on the main measures and supplementary secondary measures administered are presented in Appendix A.

Sociodemographic and health questionnaire: This questionnaire was used to collect sociodemographic information (e.g., age, gender) and information on participants' health (e.g., vestibular disorders, balance disorder, eye disease). The questionnaire was completed once before the immersions.

Behavioral measure of presence: The virtual sliding doors paradigm developed by Lepecq et al. (2009) and Mestre et al. (2016) was used to evaluate presence, which was quantified by the amplitude (in degrees) with which participants rotated their shoulders to pass through narrow virtual doors. It was hypothesized that when participants felt present, they would rotate their shoulders to pass through them. Participants' physical shoulder width was inputted into the application that ran the virtual environments to indicate where their shoulders were located in the virtual space. The application logged the rotation (in degrees) of a GameObject placed at the midpoint between participants' virtual shoulders. The output file also indicated whether a collision occurred between either or both virtual shoulders and the virtual doors. The angles were recorded relative to the participant's forward-facing direction (i.e., the direction in which they would naturally walk or look ahead). Data were logged at a rate of 20 Hz.

ITC-Sense of Presence Inventory (ITC-SOPI): This questionnaire, developed by Lessiter et al. (2001), was administered to participants after each immersion. The ITC-SOPI assessed participants' presence (e.g., "I felt I was visiting the places in the displayed environment") during (Part B; 38 items) and after (Part A; 6 items) the immersion. It comprises four subscales: Spatial Presence (19 items), Engagement (13 items), Naturalness/Ecological Validity (5 items), and Negative Effects (6 items). Each item is rated on a 5-point Likert scale (1 – *"Strongly disagree"* to 5 – *"Strongly agree"*). Subscale scores were calculated by taking the mean of corresponding items.

State-Trait Anxiety Inventory (STAI): This scale was developed by Spielberger et al. (1983) and was used to measure participants' state anxiety. It consists of two forms, each containing 20 items: form 1 assesses state anxiety and form 2 assesses trait anxiety. Only form 1 was used in this study, since the aim was to measure participants' current anxiety levels. Each item is rated on a 4-point Likert scale (1 – *"Not at all"* to 4 – *"Very much so"*) and examines participants' current feelings (e.g., "I feel calm"). Participants completed the STAI once before the immersions (baseline measure) and after each immersion. A total score was calculated by reversing the relevant items and then summing all items.

Simulator Sickness Questionnaire (SSQ): This questionnaire was developed by Kennedy et al. (1993) and assesses participants' current cybersickness symptoms. While other questionnaires exist, the SSQ was selected to ensure comparability with previous studies, as it is commonly used in VR studies. The SSQ contains 16 items with three subscales: Nausea (e.g., general discomfort, nausea), Oculomotor (e.g., eyestrain, headache), Disorientation (e.g., dizziness, vertigo). Each item is rated on a 4-point Likert scale (0 – *"None"* to 3 – *"Severe"*). The SSQ was completed once before the immersions (baseline) and after the last immersion. Following Bouchard et al.'s (2007) and Bouchard et al.'s (2021) recommendation, the items were divided into a Nausea subscale and an Oculomotor subscale and a total score for each subscale was calculated by summing the corresponding items (i.e., SSQ-Nausea-Raw and SSQ-Oculomotor-Raw). A total score for the SSQ was calculated by summing the items from both subscales (i.e., SSQ-Total-Raw). Furthermore, as per the authors' recommendation, additional subscale and total scores for the SSQ were calculated without items related to anxiety (i.e., items 1 and 9): SSQ-Nausea-Anx, SSQ-Oculomotor-Anx, and SSQ-Total-Anx.

Procedure

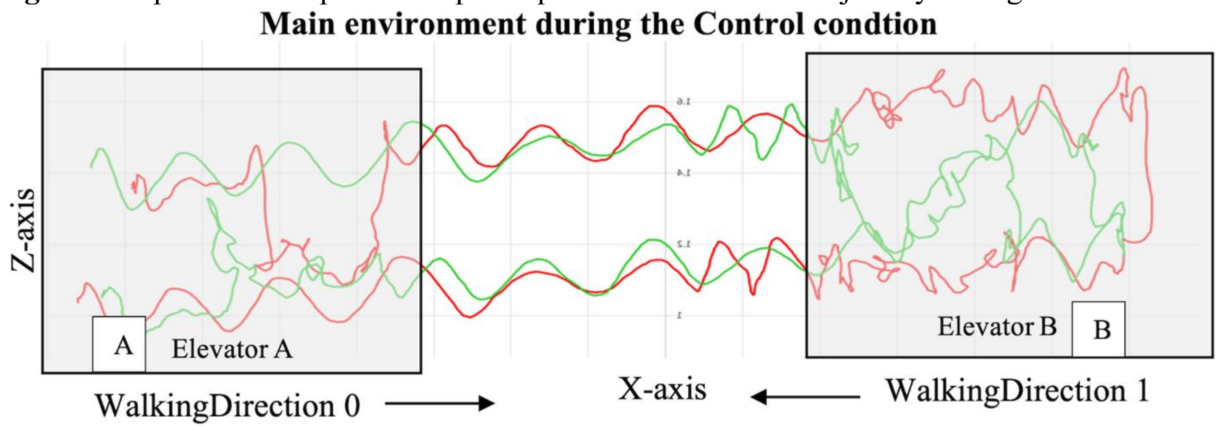
Potential participants either contacted the research team via email or signed up for the study via the University of Ottawa's Integrated System of Participation in Research (https://www.uottawa.ca/research-innovation/inspire/discover-lab/ispr-student-pool). The research team first screened participants via telephone to confirm their eligibility. Participants were then invited to the Cyberpsychology Laboratory at the Université du Québec en Outaouais to participate in the study.

The experimenter welcomed participants upon their arrival at the laboratory and briefly explained the study process. Participants then read and signed a consent form. To avoid biasing participants' behavior, only a partial objective was disclosed. Specifically, the consent form stated that the study examined presence in VR, or the feeling of "being there" in the virtual environment, but it did not indicate that participants would be exposed to a virtual height. Afterward, the experimenter measured participants' shoulder width, from the tip of one humerus to the tip of the other (for shoulder tracker calibration). Participants then completed pre-immersion online questionnaires (Sociodemographic and health questionnaire, STAI, SSQ). After they finished filling out the questionnaires, the experimenter explained the first immersion (Practice environment), asked participants to remove their footwear and helped them put on the VR equipment. Before beginning the first immersion, the experimenter calibrated the virtual environment, which involved calibrating the location of the virtual plank and the virtual feet (to match the physical counterparts) and inputting participants' physical shoulder width (to automatically adjust the virtual door aperture width) in the VR application.

This first immersion lasted approximately 2 minutes and was the same for all participants, the aim being to allow familiarization with the equipment and navigation in the virtual environment. During this immersion, participants were immersed on the ground floor of the skyscraper under construction in the practice environment. Participants' task was to walk in a straight line on the wooden plank (virtual and physical) from the starting point (point A) to a post with a virtual button and press the button (point B). Once participants pressed the button, they made a U-turn and walked back to the starting point (point A) and pressed a second virtual button (see Figure 8). After the first immersion, the experimenter answered any questions posed by the participants and explained the next immersion.

For the next three immersions, which lasted approximately 2 minutes each, all participants were exposed to the three experimental conditions in the main environment: (1) Control condition, (2) Risk of falling condition (virtual pit), and (3) Risk of falling + Fire (virtual fire). Each participant was exposed to the Control condition first, followed by the other two conditions in a randomized order. The procedure for all the immersions was identical to avoid carry-over effects of anxiety-inducing immersions on other immersions. Before each immersion (including the practice environment), participants were asked to physically walk slowly for safety reasons. Participants' task was identical to the practice environment, except that they were now inside the skyscraper under construction. Participants walked in a straight line on the wooden plank (virtual and physical) from an elevator (elevator A) to a second elevator (elevator B) and pressed a virtual button on a post. Once participants pressed the button, they made a U-turn and walked back to the first elevator (elevator A) and pressed a second virtual button (see Figure 8).

Figure 8 Top-view example of one participant's shoulders and trajectory during the task



Note. The darker red line represents the left shoulder, and the pale green line represents the right shoulder. "A" represents the approximate location of the post with the button in Elevator A and "B" the location of the post with the button in Elevator B.

Although the Practice and Main virtual environments differed, the primary difference in their behavior was that, in the Main environment, when participants reached the midpoint between elevators A and B, the virtual doors of both elevators automatically partially closed, requiring participants to pass through the narrowed apertures (with an aperture to shoulder width ratio of 0.82). The aperture of the virtual doors remained the same width for the rest of the immersion. In the Risk of falling + Fire condition, when participants pressed the virtual button, the virtual fire was extinguished. The research team decided to extinguish the fire rather than let it burn continuously to incite participants to exit elevator B and return to elevator A (participants may have chosen to remain in the elevator if the fire was not extinguished).

After each immersion, participants removed the VR equipment and filled out online questionnaires (ITC-SOPI, STAI). Once participants finished filling out the questionnaires, the experimenter explained the next immersion and helped them put on the VR equipment. Following the last immersion, participants also filled out the SSQ. In addition, a short debriefing session took place to reveal the full objectives of the study and to obtain participants' written consent a second time. The experimenter also invited participants to provide verbal feedback on their experience and suggestions for improving the virtual environment and/or the protocol.

3. Results

The data analysis was carried out in SPSS version 30.0 (IBM, 2025). First, the data were screened and cleaned by checking for data entry errors, missing values, normality, and univariate outliers. Eight participants had some missing data: six had 0.3 to 0.5% missing, and two had 2.3% and 3% missing, respectively. Since the participants had little missing data (i.e., < 5%), the missing values were imputed using the expectation-maximization (EM) method.[1] To be conservative, a separate EM run was performed for each subscale at each timepoint. All statistical analyses used the imputed data. Since the data did not follow a normal distribution and contained univariate outliers, the results from non-parametric tests are presented below.[2] Normality was assessed for each analyzed variable by visually inspecting the associated histogram (with an overlaid normal curve), verifying the skewness and kurtosis values, and carrying out the Shapiro-Wilk's test. The data were considered not normally distributed if they met at least two of the following criteria: (1) the data were visually skewed, (2) the skewness and kurtosis values were less than -1.5 or greater than 1.5, and/or (3) the p-value of the Shapiro-Wilk's test was less than .05 ($p < .05$). If a variable had several subscales (e.g., the ITC-SOPI), and the data on at least one of the subscales were not normally distributed, non-parametric tests were conducted for all subscales to avoid switching between statistical tests.

[1] Three additional participants had missing data (i.e., a total of 11 participants had missing data). However, these three participants only had missing data on the STAI (one item each), and it is recommended to compute a total STAI score with missing values. As such, these missing values were not imputed.
[2] The results from the non-parametric tests are consistent with the results from the parametric alternatives (i.e., Pearson correlations and repeated-measures ANOVAs).

Descriptive statistics were then performed, followed by inferential statistics. Note that the statistical analysis of the shoulder data included 23 participants (Control and Risk of falling + Fire conditions) and 24 participants (Risk of falling condition) whereas the statistical analysis of the questionnaire data (i.e., anxiety and presence) included 25 participants. The discrepancy in the number of participants between conditions for the analysis of the shoulder data occurred due to the shoulder trackers not recording any data for one participant in the Control and Risk of falling + Fire conditions. Since the experimentation was properly carried out (i.e., the doors closed, the participant followed instructions), and one of the study's objectives was to examine the relationship between self-reported anxiety and presence, the authors decided to include the participants' questionnaire data in the analysis to avoid losing valid data.

As per the recommendation of Bouchard et al. (2021), two sets of SSQ scores were calculated: (1) raw SSQ scores (i.e., SSQ-Raw, with items related to anxiety) and (2) corrected SSQ scores (i.e., SSQ-Anx, without the items related to anxiety). The analyses in this section were conducted using raw SSQ scores to facilitate comparisons with other studies. However, the results using corrected SSQ scores are presented in Appendix C (very similar results).

Corrections for multiple comparisons (Holm-Bonferroni) were applied within families to control the family-wise error rate. The families were defined by the study's main hypotheses. Specifically, Family 1 consisted of four variables with main hypotheses: ITC-SOPI Spatial and Naturalness subscales, shoulder rotations, and STAI. Family 2 comprised three variables from planned analyses without specific hypotheses: ITC-SOPI Engagement and Negative Effects subscales and collisions with doors. Finally, Family 3 included three variables assessed in unplanned or exploratory analyses: SSQ Nausea-Raw and Oculomotor-Raw subscales and SSQ Total-Raw score (see Appendix C). The following calculation was used for the Holm-Bonferroni correction: corrected alpha = .05/(k-m+1), where k = the number of variables in the family, m = the ranking of the variable's *p*-value in a given analysis. The raw *p*-values obtained from the statistical analyses were compared to the corrected alpha. The *p*-values only remained statistically significant if they were smaller than the corrected alpha.

First, analyses were conducted as a manipulation check to confirm that the control condition did not elicit anxiety, while the anxiety-inducing conditions did. A mean total STAI score was calculated for each experimental condition. The resulting means were extremely low (see the Discussion section for additional details): 27.40 (*SD* = 8.52) in Control, 28.45 (*SD* = 8.47) in Risk of falling, and 28.83 (*SD* = 9.21) in Risk of falling + Fire conditions. A Friedman test was then conducted (i.e., the non-parametric alternative to repeated-measures ANOVA) using the conditions as test variables. The Friedman test was not statistically significant, regardless of whether the Holm-Bonferroni correction was applied, $\chi^2_{(2)} = 1.28$, $p = .527$.[3] A Friedman test was also performed with the STAI score at pre (*M* = 28.62, *SD* = 6.86) as an additional test variable to assess whether incorporating this time point affected the results. However, this test was not statistically significant either, regardless of whether the Holm-Bonferroni correction was applied: $\chi^2_{(3)} = 4.79$, $p = .188$.

To examine participants' shoulder rotations in the two areas of interest, a mean shoulder rotation angle for each participant within each condition was computed with Python scripts. Appendix B contains details on the process for data cleaning and extraction. The main steps for extracting the data included (1) visualizing the data, (2) preprocessing the data, (3) identifying the areas of interest (i.e., first shoulder approaching the doorway until this shoulder has entered

[3] Participants' walking patterns were analyzed (e.g., time taken to walk from elevator A to elevator B and vice versa, walking speed). However, there were no statistically significant differences between the conditions. The results are not presented or discussed in this paper.

the doorway), and (4) extracting and analyzing the data. The first step involved generating 2D and 3D plots to visualize the spread of data and determine whether the data contained abnormal values (large spikes in the plots, where a value differed from surrounding values). During the second step, outliers were identified and removed using the interquartile method (IQR). Specifically, if data points were outside of the IQR range, they were removed. Since the aim of the study was to examine whether participants generally rotated their shoulders when passing through the narrow virtual doors (rather than precise biomechanical movement), the IQR method was deemed appropriate for outlier detection and removal. In the third step, areas of interest for each participant and condition were identified using a column in the data indicating when their shoulders were in the doorway, as the virtual environment did not record the exact location of the virtual doors during the experimentation. Finally, the last step involved extracting the data based on the areas of interest and analyzing the data, including normalizing the shoulder rotation angles from a 0 to 360-degree range to a 0 to 180-degree range, identifying maximum shoulder rotation angles, and computing the mean shoulder angles in the areas of interest (i.e., the mean of the maximum shoulder rotation angle for elevator A and the maximum shoulder rotation angle for elevator B). For additional details on the steps followed, see Appendix B.

Table 1 contains the mean shoulder rotation angles in each experimental condition. The discrepancy in sample size between conditions for the analysis of shoulder data occurred due to the shoulder trackers not recording any data for one participant in the Control and Risk of falling + Fire conditions.

Table 1 Descriptive statistics of shoulder rotation angles per experimental condition

Condition	*M*	*Mdn*	*SD*	Minimum	Maximum
Control	44.64	46.36	24.15	7.24	85.42
Risk of falling	46.22	52.01	24.47	8.66	82.35
Risk of falling + Fire	46.90	46.54	28.91	5.91	98.02

Note. **Control** condition: $n = 23$; **Risk of falling** condition: $n = 24$; **Risk of falling + Fire** condition: $n = 23$.

Collisions with the virtual doors were also counted for each experimental condition in the two areas of interest (see Table 2). Collisions were defined in the following manner: No collisions = did not collide with the doors of either elevator (i.e., neither A nor B); One collision = collided with the doors of one elevator (i.e., A or B); Two collisions = collided with the doors of both elevators (i.e., A and B). Since there were two elevators, the maximum possible frequency of collisions for each participant is 2. In the Control condition, few participants (n = 6; 26.09%) collided with the doors of either elevator. For the Risk of falling condition, most participants (n = 22; 91.67%) collided with the doors of at least one elevator. Finally, the results for the Risk of falling + Fire condition were similar, with 23 participants (100.00%) colliding with the doors of at least one elevator. A Friedman test was performed using the conditions as test variables. The Friedman test was statistically significant, $\chi^2_{(2)} = 36.55$, $p < .001$. Wilcoxon signed ranks tests were then conducted (non-parametric alternative to post-hoc tests). The frequency of collisions was significantly different between the Control and the Risk of falling conditions ($Z = -4.14$, $p < .001$) and between the Control and the Risk of falling + Fire conditions ($Z = -4.10$, $p < .001$), but not between the Risk of falling and the Risk of falling + Fire conditions ($Z = -.26$, $p = .792$). The results remained statistically significant after applying the Holm-Bonferroni correction: corrected alpha = .05/(3-1+1) = 0.017 (rounded).

Table 2 Frequency of participants who collided with the doors per experimental condition

Condition	No collisions	One collision	Two collisions
Control	17 (73.91%)	6 (26.09%)	0 (0.00%)
Risk of falling	2 (8.33%)	3 (12.50%)	19 (79.17%)
Risk of falling + Fire	0 (0.00%)	4 (17.39%)	19 (82.61%)

Note. **Control** condition: n = 23; **Risk of falling** condition: n = 24; **Risk of falling + Fire** condition: n = 23. Results are presented as frequency followed by percentage in parentheses. No collisions = did not collide with the doors of either elevator (i.e., neither A nor B). One collision = collided with the doors of one elevator (i.e., A or B). Two collisions = collided with the doors of both elevators (i.e., A and B).

To analyze whether shoulder rotation angles correlated with self-report measures of presence, Spearman correlations were performed.[4] Table 3 contains descriptive statistics from self-report measures for each experimental condition. The results of the Spearman correlations showed the correlation between shoulder rotation angles and self-report measures of presence was not statistically significant (regardless of whether the Holm-Bonferroni correction was applied) in any of the experimental conditions (see Appendix C and Table 4).

Table 3 Descriptive statistics of questionnaire scores per experimental condition (*n* = 25)

Variable	Control			Risk of falling			Risk of falling + Fire		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*	*M*	*Mdn*	*SD*
STAI	27.40	25.00	8.52	28.45	26.00	8.47	28.83	26.00	9.21
ITC-SOPI–Spatial	3.59	3.39	.54	3.53	3.56	.62	3.55	3.44	.62
ITC-SOPI–Engagement	3.64	3.54	.55	3.54	3.54	.52	3.57	3.62	.51
ITC-SOPI–Naturalness	3.45	3.60	.89	3.51	3.60	.77	3.39	3.40	.89
ITC-SOPI–Neg. Effects	1.43	1.17	.55	1.49	1.33	.61	1.46	1.33	.54
	Pre						Post		
	M	*Mdn*	*SD*				*M*	*Mdn*	*SD*
SSQ–Nausea-Raw	.24	.00	.52				.32	.00	.56
SSQ–Oculomotor-Raw	1.16	1.00	1.25				1.48	.00	2.38
SSQ–Total-Raw	1.40	1.00	1.41				1.80	1.00	2.50

Note. Participants completed the SSQ before the first immersion and after the last immersion.

Furthermore, there was no statistically significant correlation between the self-report measures of presence and anxiety (regardless of whether the Holm-Bonferroni correction was applied) in any of the experimental conditions (see Table 4). Interestingly, the correlation between shoulder rotation angles and ITC-SOPI–Negative Effects (or cybersickness) was statistically significant (see Table 4). However, the result was no longer significant after applying the Holm-Bonferroni correction: corrected alpha = .05/(3-1+1) = 0.017 (rounded).

[4] The correlations reported in the paper were not adjusted for reliability (i.e., the observed/attenuated correlations are presented). However, the correlations adjusted for reliability (i.e., disattenuated correlations) were very similar. For additional details, please contact the corresponding author.

Table 4 Spearman correlations between shoulder rotation angles, anxiety, and presence

Condition and Variable	1	2	3	4	5	6
Control						
1. Shoulder Rotation Angle	–					
2. STAI	.00	–				
3. ITC-SOPI–Spatial	.04	-.11	–			
4. ITC-SOPI–Engagement	.10	.05	**.77****	–		
5. ITC-SOPI–Naturalness	-.15	.04	**.66****	**.57****	–	
6. ITC-SOPI–Neg. Effects	**-.45***	**.43***	-.17	-.06	-.06	–
Risk of falling						
1. Shoulder Rotation Angle	–					
2. STAI	-.23	–				
3. ITC-SOPI–Spatial	.25	.04	–			
4. ITC-SOPI–Engagement	.24	-.35	**.52****	–		
5. ITC-SOPI–Naturalness	.05	-.06	**.70****	**.50***	–	
6. ITC-SOPI–Neg. Effects	**-.49***	**.49***	-.27	-.14	-.37	–
Risk of falling + Fire						
1. Shoulder Rotation Angle	–					
2. STAI	-.27	–				
3. ITC-SOPI–Spatial	.01	.14	–			
4. ITC-SOPI–Engagement	.20	-.25	**.59****	–		
5. ITC-SOPI–Naturalness	-.26	.18	**.78****	.39	–	
6. ITC-SOPI–Neg. Effects	-.22	.34	-.27	-.25	-.15	–

Note. **Control** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles; **Risk of falling** condition: $n = 25$ for questionnaires and $n = 24$ for shoulder rotation angles; **Risk of falling + Fire** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles.
$^*p < .05$. $^{**}p < .01$.

In addition, the results indicated several statistically significant correlations between the SSQ-Raw (subscales and total scores) and the STAI and the ITC-SOPI subscales. For the Control condition, a significant correlation was found between the SSQ Nausea-Raw subscale and the ITC-SOPI Spatial Presence subscale. For the Risk of falling condition, the following correlations were significant: (1) SSQ Oculomotor-Raw and STAI, (2) SSQ Total-Raw and STAI, (3) SSQ Nausea-Raw and ITC-SOPI Naturalness, (4) SSQ Oculomotor-Raw and ITC-SOPI Engagement, (5) SSQ Oculomotor-Raw and Naturalness, and (6) SSQ Total-Raw and ITC-SOPI Engagement. Finally, for the Risk of falling + Fire condition, there was a significant correlation between: (1) SSQ Nausea-Raw and STAI, (2) SSQ Total-Raw and STAI, and (3) SSQ Oculomotor-Raw and ITC-SOPI Spatial Presence. However, many of the correlations were no longer significant after applying the Holm-Bonferroni correction. Appendix C presents the full correlation table, including SSQ-Anx scores.

To test the hypothesis that the Risk of falling + Fire condition would induce higher presence than the Risk of falling condition, Friedman tests were performed. The test variables were the experimental conditions (Control, Risk of falling, and Risk of falling + Fire). None of the Friedman tests were significant, regardless of whether the Holm-Bonferroni correction was applied: Spatial Presence ($\chi^2_{(2)} = .41$, $p = .815$), Engagement ($\chi^2_{(2)} = .36$, $p = .835$), Naturalness ($\chi^2_{(2)} = .10$, $p = .953$), and Negative Effects ($\chi^2_{(2)} = .24$, $p = .888$).

4. Discussion

The current study assessed whether the amplitude of shoulder rotations could be used as a measure of behavioral presence based on Lepecq et al.'s (2009) and Mestre et al.'s (2016) virtual sliding doors paradigm. The relationship between presence and anxiety was also assessed through exposure to heights and fire. The following hypotheses were put forward: (1) participants will rotate their shoulders to pass through the virtual doors when they feel present, (2) the amplitude, or angle (in degrees), of the shoulder rotation will correlate with the self-report measure of presence, (3) the behavioral measure of presence (i.e., shoulder rotation) will correlate significantly with the measure of anxiety, and (4) presence will be highest in the condition expected to induce higher anxiety.

The results partially supported Hypothesis 1. Participants all rotated their shoulders to some degree to cross the narrow virtual doors (see Appendix C). However, the amplitude of shoulder rotations varied between participants, where some participants made a relatively large shoulder rotation (e.g., approximately 90°) whereas others made a smaller shoulder rotation (e.g., approximately 20°). In addition, most participants collided with the doors, even though they made a larger shoulder rotation. This might be due to distance compression, where users tend to overestimate the distance between objects or between themselves and objects in VR (Buck et al., 2021). In the current study, participants may have perceived the space between the doors as large enough to pass through without needing to make a large shoulder rotation. It is possible that the absence of a virtual body made it difficult for participants to judge the position of their shoulders and the required rotation to pass through the doors. Previous studies conducted in VR (e.g., Lepecq et al., 2009; Mestre et al., 2016) and in the physical environment (e.g., Warren & Whang, 1987; Wilmut & Barnett, 2010; Wilmut, Du, & Barnett, 2015) reported mean maximum shoulder rotations between 40 and 90° when the aperture to shoulder (A/S) or shoulder to aperture (S/A) ratio was 1.3 or less. In the current study, the mean maximum shoulder rotations were approximately 45°. The studies used different motion tracking equipment (motion capture equipment versus VIVE trackers), environments (CAVE or physical environment versus VR headset), and experimental tasks (different aperture widths versus constant width).

The frequency of shoulder collisions with the elevator doors differed significantly between conditions, with much fewer collisions in the Control condition compared to the Risk of falling and the Risk of falling + Fire conditions. It is possible that participants were paying attention to the virtual pit and fire, which may have resulted in reduced awareness of their peripheral surroundings and a "misjudgment" about the passability of the narrow doors. While previous studies have not specifically examined the perception of doorway aperture passability in fearful conditions, they have shown that fear can influence distance perception and perceived affordances in both physical and virtual environments (Geuss et al., 2016; Graydon et al., 2012;

Stefanucci & Proffitt, 2009). Moreover, since the Control condition was always completed first, participants may have realized that there were no consequences in the physical environment, making them less cautious when crossing the narrow doors in subsequent conditions.

The second hypothesis supposed that a larger shoulder rotation would represent higher presence, but the results from the correlation analysis showed that the amplitude of shoulder rotation did not significantly correlate with self-report measures of presence. Interestingly, participants performed other behaviors that suggested that they still felt present. For example, some participants reached out with their physical hands when they arrived in front of the narrow virtual doors and made a "sweeping" motion their hands in front of them. It is unclear whether participants did this to feel if the virtual doors were "actually there" in the physical environment or they were trying to prevent the virtual doors from closing further. It is not possible to determine why participants made this motion with their hands, as the experimenter did not ask for participants' feedback on this. Some participants also compressed their shoulders and made a small shoulder rotation (e.g., 20°) rather than completely rotating their shoulders (90°) to pass through the narrow doors. It is unclear whether these participants would behave similarly in the physical environment or if this was an artifact of VR.

In two studies, Beacco et al. (2021) and Slater et al. (2023) examined participants' responses while they were immersed in a virtual rock concert. A virtual audience surrounded participants to increase the realism of the scenario. Interestingly, the results revealed that the audience led to a negative sentiment in some participants (e.g., feeling stared at). While this result was unexpected, the authors argued that it indicated high plausibility, as participants would only react in this manner if they felt like the events in the virtual environment were actually occurring (plausibility illusion). Similarly in the current study, despite the amplitude of shoulder rotations not significantly correlating with presence, participants still seemed to demonstrate a certain level of presence through unexpected behaviors, such as trying to open the virtual doors with their physical hands.

The current study used shoulder rotations as a behavioral measure of presence to avoid relying on reflex-like responses (e.g., throwing a virtual object at participants' heads and assess whether they "duck"), which may be automatic and not specific to humans (Mestre, 2015; Mestre & Fuchs, 2006). In addition, the sliding door paradigm has been validated by both Lepecq et al. (2009) and Mestre et al. (2016), though neither study measured self-reported presence. The paradigm has also been validated in an anxiety-inducing scenario in the physical environment. Specifically, Hackney et al. (2015) showed that the magnitude of shoulder rotations when crossing a narrow aperture was smaller in the condition at heights than in the condition on the ground, which suggests that postural threats such as heights have an impact on shoulder rotations. While the current study did not find a significant correlation between self-reported presence and the amplitude of shoulder rotation in any of the experimental conditions, the study provides preliminary insights and highlights areas for improvement. It could be useful in future work to use different behavioral measures to assess other behaviors that can occur in anxiety-inducing environments, such as reduced walking speed and shorter steps.

One reason why some participants made smaller shoulder rotations could be that the virtual environment contained elements that were not believable (e.g., the virtual hands going through the virtual door if participants touched the door, the absence of a virtual body). One participant reported finding the virtual doors' behavior unrealistic – specifically, when they tried to push the doors open with their hands, the doors did not move. Some participants also found the ambient city sounds in the virtual environment unrealistic. Furthermore, participants mentioned still being aware of their surroundings (i.e., the laboratory) and knowing that they were safe and would not fall if they stepped off the plank (i.e., they knew that there was a physical floor beneath the plank). The absence of a virtual body likely also reduced the realism of the virtual environment. Previous studies have shown that an embodied self-avatar can affect size and distance perception (e.g., van der Hoort & Ehrsson, 2014).

Multisensory integration plays a key role in inducing presence. Previous studies suggest that congruent multisensory stimulation can enhance presence (e.g., Dinh et al., 1999). It is possible that the lack of haptic feedback informing participants when they collided with the virtual doors impacted their behavior. For example, Mestre et al. (2016) replicated the results from Lepecq et al.'s (2009) study, except that they included haptic, visual, and auditory feedback when participants were about to collide or collided with the virtual doors. Participants were also immersed using a VR headset rather than a CAVE, as was the case for Lepecq et al's study. Mestre et al.'s (2016) study had the following four experimental conditions: vibrotactile feedback only (vibration of controllers), visual feedback only (full body co-located self-avatar with spheres over shoulders), vibrotactile + visual feedback, and no feedback (no body representation and no vibration). Participants completed all conditions in a randomized order and walked through five aperture widths (40, 50, 60, 70, and 80 cm; each aperture width was repeated four times). The results revealed that overall, the mean maximum shoulder rotations were larger when both vibrotactile and visual feedback were included. Participants also tended to collide more frequently while crossing the aperture when only visual feedback (no vibrotactile feedback) was included. Considering these results, the next study will include vibrotactile (haptic) feedback.

Hypothesis 3 stated that the behavioral measure of presence would significantly correlate with self-reported anxiety. This hypothesis was not supported: the correlation between anxiety and presence was not statistically significant. These results are consistent with some previous studies (e.g., Bouchard et al., 2008 for the results from the questionnaires). However, many previous studies found a significant correlation between presence and anxiety (e.g., Gromer et al., 2019; Kisker et al., 2021; Robillard et al., 2003). The results of the current study might be due to low mean total STAI scores, which were 27.40 (Control), 28.45 (Risk of falling), and 28.83 (Risk of falling + Fire). The lack of difference between the conditions suggests that the manipulation of anxiety was not effective in increasing self-reported anxiety. Total scores of the STAI (whether the Trait or State subscale) can range from a minimum score of 20 to a maximum score of 80. Total scores between 20 and 37 represent "no or low anxiety", scores between 38 and 44 represent "moderate anxiety", and scores between 45 and 80 represent "high anxiety" (Kayikcioglu et al., 2017; Spielberger et al., 1983). In the current study, some participants may have looked ahead (rather than down) during the Risk of falling and Risk of falling + Fire conditions, which could have led to lower anxiety scores. Furthermore, convenience sampling may have contributed to these low scores. Due to challenges with participant recruitment, the experimenters knew several participants and vice versa, which could have resulted in a social desirability effect where participants reported lower anxiety than they actually experienced. During the next study, the research team will aim to recruit participants that do not know the experimenters.

Although the STAI scores were low, the ITC-SOPI scores were consistent with the results in previous studies, which obtained mean scores between 2 and 4 for the Spatial Presence, Engagement, and Naturalness subscales and mean scores of 2 or less for the Negative Effects subscale (e.g., Freeman et al., 2005; Lessiter et al., 2001). The questionnaires in the current study were completed post-immersion, outside of VR, which may have had an impact on presence and anxiety, as they were assessed retrospectively. The research team chose this method, as the questionnaires were relatively long. Moreover, this method allowed to compare the study's results with other studies where participants also completed questionnaires post-immersion, outside of VR (e.g., Bouchard et al., 2008; Gromer et al., 2019; Kisker et al., 2021). However, it would be useful for future studies to administer questionnaires only once after one longer, continuous immersion or integrate a brief assessment directly within the virtual environment to avoid interrupting participants' experience.

The results also did not support Hypothesis 4. The results indicated that participants did not experience significantly higher presence in the Risk of falling + Fire condition than in the Control or the Risk of falling condition. Many participants reported not finding the Risk of falling condition or the Risk of falling + Fire condition anxiety-inducing. Two participants suggested making the scenarios more fearful. In the next study, the virtual environment will be modified to amplify the perception of height. Regarding the Risk of falling + Fire condition specifically, many participants reported finding the virtual fire's appearance and behavior unnatural and unrealistic (e.g., fire spreading in an unnatural manner, too little charring and smoke). Some participants also found that the virtual environment lacked visual realism and felt like they were immersed in a video game and that the task during the Risk of falling + Fire condition did not make sense. One participant wondered if this condition was a behavioral test assessing whether they would turn around and return to the elevator because in the physical environment, one would not walk through a burning building unless they were evacuating. This difference between the virtual environment and the physical environment might have decreased the believability of the scenario, and thus, presence. Few participants had prior experience with VR, which may have contributed to high expectations of the virtual environment. When it did not meet their expectations, participants may have experienced lower presence.

In summary, the results did not support the hypotheses. The lack of physical consequences and mismatch between participants' expectations and behavior and appearance of the virtual environment likely contributed to the results. Since the virtual environment seemed to represent a realistic scenario, a participant's hand passing through the virtual door is not realistic and does not match one's expectations of what would occur in the physical environment. In other words, if participants perceive the virtual environment as not believable, it could diminish their presence and impact their behavior (Berthiaume et al., 2018).

Exploratory analyses revealed a significant correlation between the STAI and the Negative Effects subscale of the ITC-SOPI in the Control and Risk of falling conditions. The results also found a significant correlation between the STAI and the SSQ Total-Raw score. Mean SSQ-Raw scores on both the Nausea and Oculomotor subscales were below 2 in the current study. These low scores were likely a result of participants walking slowly during the immersions and not making large or quick head movements. In the next study, the relationship between anxiety, presence, and cybersickness will be further examined.

It is possible that behavioral indicators of presence (users' actions) do not necessarily align with self-reported presence. Specifically, the self-report and behavioral measures of presence in VR may show a pattern of discordance, a phenomenon in psychology where the correlation between self-report and behavioral measures is not statistically significant. Previous studies suggest that self-reported fear and avoidance behavior may not necessarily converge (e.g., Hodgson & Rachman, 1974; Rachman & Hodgson, 1974). For example, individuals may report a high fear of heights but not engage in strong avoidance of situations involving heights. In their systematic review, Ernst et al. (2024) found a similar effect between self-reported and physiological symptoms of anxiety in VR-based exposure treatments. In two studies, Maymon et al. (2024) revealed a non-significant relationship between self-reported presence and physiological responses (heart rate and skin conductance) when participants were exposed to a virtual height. However, there was a significant relationship between self-reported presence and anxiety. Incorporating multiple measures of presence can provide a more comprehensive understanding of users' experiences in virtual environments and can help validate or contextualize self-report data and study results. Berthiaume et al. (submitted) explored in another study whether self-report and behavioral measures of presence in VR actually show a pattern of discordance.

Limitations and future directions

The current study has some limitations. One limitation is that the equipment used to install the trackers over participants' physical shoulders was not customized to each participant. During the study, participants wore a pack frame with a metal rod attached to it, which held the trackers over their shoulders. During the calibration of the virtual environment, the experimenter inputted participants' physical shoulder width. This decision was made for practical reasons. Rather than using motion capture equipment, the research team decided to use VIVE trackers as they were also using a VIVE headset. In addition, since the objective of the study was to measure the amplitude of shoulder rotations rather than very precise biomechanical or motion data, the pack frame was considered an appropriate option. A few participants reported being aware of the pack frame during the immersions. However, the pack frame was narrower than all participants' physical shoulders – thus, it should not have affected their shoulder rotations. Future studies could use motion capture and compare the results with a pack frame.

Another limitation is that the virtual environment did not include any visual cues, such as a virtual body. Previous studies have shown that having a virtual body provides a sense of embodiment and of spatial location in the virtual environment (e.g., Mestre et al., 2016). The current study only included virtual hands and feet as the experimental task did not require participants to have a full virtual body (e.g., study on body image distortion). Gonçalves et al. (2022) showed that only having virtual hands and feet is sufficient for participants to feel present in the virtual environment. In addition, designing a believable full body avatar is challenging, since any technical issues, unnatural movement, or not meeting users' expectations could reduce their presence (Berthiaume et al., 2018). Future studies could include virtual objects to represent participants' shoulders.

Finally, the virtual environment did not contain any sensory information to indicate that a participant had collided with the virtual doors. Including auditory (e.g., a "thud" sound) and/or haptic (e.g., vibrations) feedback when the participant collides with the virtual doors, such as Bhargava et al. (2023), Mestre et al. (2016), and Ribé-Viñes et al. (2025), could increase the realism of the virtual environment and potentially encourage participants to behave more similarly to how they would in the physical environment. One challenge with VR, and the current study, is that there is often sensory information missing when a user interacts with the virtual environment (e.g., when a user lifts an object, they will not feel its weight or if they collide with furniture in VR, they will "go through" the object unless it has a collider). In other words, there are often no physical consequences to users' actions in VR, which is not the case in the physical environment. It would be interesting in a future study to compare the results between VR and the physical environment.

5. Conclusion

Few studies have used both behavioral and self-report measures of presence in a context of anxiety in VR. The current study mainly aimed to evaluate a behavioral measure of presence in VR. Specifically, the study investigated whether participants physically rotated their shoulders to cross narrow virtual sliding doors, while anxiety was experimentally manipulated. In addition, the study assessed self-reported presence, anxiety, and cybersickness. The results showed that participants physically rotated their shoulders to cross the narrow doors, but unexpected behaviors were also observed, such as some participants trying to touch the doors with their hands. Furthermore, the correlation between the behavioral and self-report measures of presence, as well as between presence and anxiety, was not statistically significant. However, cybersickness and anxiety were significantly correlated. Although the relationship between presence and anxiety was not statistically significant, the results provide directions for future research, which will be further explored in a second study.

Enhancing users' presence may increase the likelihood that they behave more realistically in VR. Users not feeling present could pose challenges for virtual environments designed to elicit naturalistic behavior, such as virtual environments used for training or clinical applications. One potential method for improving the realism of the virtual environment is to incorporate multisensory stimulation, such as haptic feedback. In addition, incorporating multiple measures of presence can help researchers and developers evaluate the effectiveness of virtual environments and provide a deeper understanding of users' experiences.

6. References

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Appendix A

Supplementary information on main measures & secondary measures

Below are additional details on the measures presented in the main paper, as well as a list of supplementary secondary measures administered during the study. The secondary measures were not presented in the main paper as they were not part of the main analyses.

Main measures

ITC-Sense of Presence Inventory (ITC-SOPI): The ITC-SOPI is commonly used in research and has been well validated. The Naturalness/Ecological Validity subscale allowed to measure the plausibility illusion (i.e., the perceived believability of the VEs and the feeling that the events in the VEs are actually occurring). Cronbach's alphas for the subscales are as follows: 0.76 (Naturalness/Ecological Validity), 0.77 (Negative Effects), 0.89 (Engagement), and 0.94 (Spatial Presence). The Cyberpsychology Laboratory of the Université du Québec en Outaouais (2006) performed a free translation ("*traduction libre*") of the questionnaire to French.

State-Trait Anxiety Inventory (STAI): The STAI possesses good internal consistency (internal consistency coefficients have ranged from .86 to .95) and test-retest reliability (*r* has ranged from .65 to .89; Spielberger et al., 1983; Spielberger, 1989). It has also shown good construct and concurrent validity (Spielberger, 1989). Gauthier and Bouchard (1993) translated and validated the French version of the scale. This version has also shown good construct validity and internal consistency (Cronbach's alpha of .90 for form 1 and .91 for form 2).

Simulator Sickness Questionnaire (SSQ): Bouchard, Robillard, and Renaud (2007) translated and validated the French version of the SSQ. It possesses good internal consistency: Cronbach's alpha has ranged from .86 to .87 (Bouchard et al., 2007; Bouchard et al., 2009; Bouchard et al., 2011).

Secondary measures

Presence and Reality Judgment Questionnaire: This questionnaire was developed by Baños et al. (2005) and was validated in previous studies (Baños et al., 2005; Quero et al., 2008). The questionnaire contains questions on presence (e.g., "I felt I "was" physically in the virtual world") and the level of realism of the virtual environment (e.g., "What I saw in the virtual world was similar to reality"). It was selected because it includes many items on subjective/perceived realism (to what extent participants find the virtual environment credible and real). Other questionnaires (including the ITC-SOPI) do not assess subjective/perceived realism as extensively. Only the items inquiring about subjective/perceived realism were used (14 items), which are rated on a 10-point Likert scale (0 – *"I don't agree"* to 10 – *"I totally agree"*). The Cyberpsychology Laboratory of the Université du Québec en Outaouais (2005) performed a free translation ("*traduction libre*") of the questionnaire to French. The questionnaire was completed after each immersion. A total score was calculated by summing all the items.

Immersive Tendencies Questionnaire (ITQ): This questionnaire was developed by Witmer and Singer (1998) and examines participants' tendency to feel absorbed when they do certain activities (e.g., watching a movie, playing a video game, playing sports) and how they currently feel (e.g., how mentally alert they feel, how physically fit they feel). The questionnaire has 18 items with four subscales: Focus, Involvement, Emotions, and Games. Each item is rated on an 8-point Likert scale (0 – *"Never"* to 8 – *"Often"*). The French version of the questionnaire has good internal reliability (Cronbach's alpha of .78) and content and construct validity (Robillard et al., 2002). Participants completed the ITQ before the first immersion.

Acrophobia Questionnaire (AQ): This questionnaire was developed by Cohen (1977) and was used to assess the fear of heights (e.g., "Riding a Ferris wheel."). It comprises two scales (total of 40 items): (1) Anxiety Scale (20 items) and (2) Avoidance Scale (20 items). The Anxiety Scale is rated on a 7-point Likert scale (0 – *"Not at all anxious; calm and relaxed"* to 6 – *"Extremely anxious"*). The Avoidance Scale is rated on a 3-point Likert scale (0 – *"Would not avoid doing it"* to 2 – *"Would not do it under any circumstances"*). The AQ has good internal consistency and test-retest reliability (median $r = .82$; Cohen, 1977). The Cyberpsychology Laboratory of UQO (2003) performed a free translation ("*traduction libre*") of the questionnaire. The AQ was completed after the last immersion.

Body Shape Questionnaire (BSQ-8B): The original version of the BSQ was developed by Cooper et al. (1987). Evans and Dolan (1993) developed the 8-item version B of the BSQ, which was used in the current study. It assesses whether participants have body dissatisfaction, which could affect the amplitude of their shoulder rotations: if a participant perceives that they are larger than they actually are, they could exaggerate their shoulder rotations when they walk through the virtual doors. This would not be a sign of higher presence, but of body image distortion. The BSQ-8B is rated on a 6-point Likert scale (1 – "*Never*" to 6 – "*Always*"). It has good internal consistency (Cronbach's alpha of .87) and convergent and discriminant validity (Evans & Dolan, 1993). The questionnaire was completed after the last immersion. Lentillon-Kaestner et al. (2014) translated the BSQ-8B to French and found good concurrent validity, test-retest reliability ($r \geq .97$), and internal consistency (Cronbach's alpha of .71).

Physiological measures: Heart rate and skin conductance are known measures of physiological arousal related to anxiety and were used as a manipulation check to validate the experimental conditions. Heart rate was measured using a Polar chest strap with electrodes worn beneath clothing (participants placed the strap themselves). Skin conductance was measured using Velcro electrodes from Thought Technology placed on the index and ring fingers of participants' non-dominant hand.

The heart rate and skin conductance devices were connected to the ProComp Infinity™ wireless device from Thought Technology, which transmitted physiological data to a second desktop computer running on Windows 10 Education (Intel® Core™ i7-4790 CPU @ 3.60GHz, 16 GB RAM, 64-bit operating system). Thought Technology's BioGraph Infiniti Software recorded the physiological data.

Before beginning the immersions in VR, the experimenter helped participants put on the physiological equipment and calibrated the instruments. A short baseline measure was then taken (approximately 2 minutes). The physiological data was recorded continuously during the entire experimentation.

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Appendix B

VR shoulder data preprocessing and analysis

This appendix describes the steps followed to preprocess and analyze the shoulder rotation data obtained from Unity. Specifically, VIVE shoulder trackers were installed over the left and right shoulders and recorded shoulder positions (coordinates) on the X, Y, and Z axes during the VR experiment. Unity recorded 20 data points per second. The number of data points recorded per second might fluctuate slightly due to variations in the amount of time elapsed between each frame (Unity, 2021).

Visual inspection of interactive 3D plots and of recordings of participant trajectories in a Unity visualization application showed that the data required preprocessing as there were multiple anomalous data points (e.g., large deviations between data points on the Y-axis when there were technical issues with the shoulder trackers). The sections below provide additional details about the procedure that was followed for preprocessing and analyzing the data. The Python scripts referred to in the next sections contain additional notes about the procedure followed.

Cartesian coordinate systems

Unity uses a left-handed Cartesian coordinate system where the Y-axis represents up-down. In some Cartesian coordinate systems, the Y-axis represents up-down whereas in others, the Z-axis represents up-down. This affects the interpretation of each axis. Specifically, in a coordinate system where the Y-axis is up-down (such as Unity), the Y coordinates represent vertical displacement, and the Z coordinates represent horizontal displacement. In a coordinate system where the Z-axis is up-down (such as Unreal Engine), the Z coordinates represent vertical displacement, and the Y coordinates represent horizontal displacement. Since the current study uses Unity, any changes on the Y-axis represent up-down movement (e.g., bending over).

Python variable names

This section lists the main variable names used in the Python scripts:

- ParticipantID: An individual participant's ID number.
- EVCondition: The current experimental condition (i.e., Control, Height, or Height_Fire).
- WalkingDirection: The direction of walking, where 0 = Door A to Door B ("Going"); 1 = Door B to Door A ("Returning").
- DoorName: The name of the doorway/elevator being entered or exited (i.e., Door A or Door B).

Step 1: Plot data

The data were first visualized using the Python scripts "00_plot_shoulder_data_3D.py" (interactive 3D plot) and "01_plot_shoulder_data_2D.py" (interactive 2D plot). See the scripts for additional details. This step used the original/unprocessed data.

The 3D plots generated by the Python script were visually inspected and recordings of individual trajectories were viewed in a Unity visualization application created by the lead developer at the laboratory. Several participants with anomalous data points were identified (see Table 5).

Table 5 Participants with anomalous data points following the inspection of 3D plots and recordings of individual trajectories (unprocessed data)

Participant ID	Condition(s)
04	Height, Height_Fire
05	Height_Fire
08	Height, Height_Fire
09	Control, Height, Height_Fire
14	Control, Height, Height_Fire
15	Control, Height, Height_Fire

20	Height, Height_Fire
22	Control, Height, Height_Fire
23	Control, Height_Fire
24	Control, Height
25	Height
27	Control
31	Height, Height_Fire
34	Control, Height, Height_Fire

Step 2: Preprocess data

Following the visualization of the data in Python and in Unity, the data were preprocessed using the Python script “02_shoulder_data_preprocess_IQR.py”, which automated the data cleaning. Then, plots were generated again using the preprocessed data. The Python script followed the steps below (see the script for additional details):

1. Drop rows containing extreme left and right shoulder tracker positions on the Y-axis[5] (i.e., smaller or larger than the median ± 0.4) for each participant.
2. Compute the interquartile range (IQR) for the left and right shoulder tracker positions for each participant.
3. Drop rows containing data points that fall below the lower bound (Q1 - IQR * multiplier) or above the upper bound (Q3 + IQR * multiplier), which are considered outliers, for each participant.
    a. A dynamic multiplier was used to adjust filtering strictness based on natural variability in shoulder movement and IQR size, accounting for individual differences. This approach prevents both over-filtering and under-filtering while removing outliers. For example, if a participant shows higher natural variability in shoulder movement, a fixed smaller multiplier may incorrectly classify valid data

[5] By visually inspecting the 3D plots, it was determined that most outliers were located on the Y-axis.

points as outliers. Conversely, if a participant has lower natural variability, a fixed larger multiplier may incorrectly classify outliers as valid data points (Ramsey et al., 2011). By using a dynamic multiplier, the filtering method adapts to individual differences, ensuring that outliers are removed while retaining as many valid data points as possible.

4. Visually inspect the interactive 3D plots with preprocessed data to confirm that outliers were removed. (The script plots the data before and after the IQR filter is applied.)
5. For participants who still have noticeable outliers, manually drop rows containing outlying values (see Python script for more details).

Step 3: Identify areas of interest

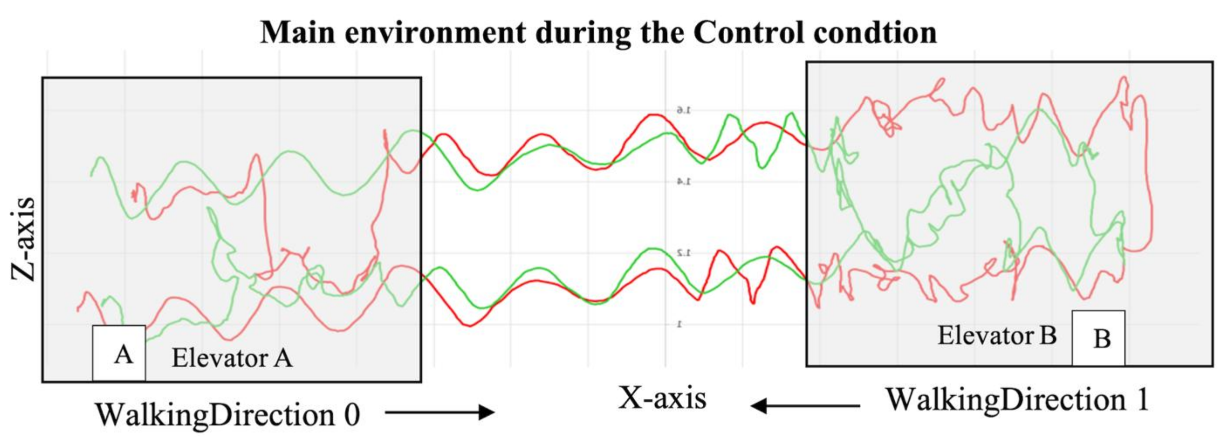
The areas of interest for each combination of participant (ParticipantID), condition (EVCondition), walking direction (WalkingDirection), and doorway (DoorName) were identified using the unprocessed data[6] and the Python script "03_shoulder_data_doorways.py". The identified areas of interest were used to filter the shoulder data in the next step. Note that the position of the doors in Unity during the experimentation was not recorded. The areas of interest were identified based on when the participants' shoulders were in the doorway. Areas when the participant was near (i.e., 1.5 seconds before entering the doorway) and in the doorways were highlighted in color using the Python script "03_shoulder_data_doorways.py". Afterwards, the data points in the output file "03_start_end_doorways_positions.csv" and the data points highlighted in the 3D plots were compared to confirm that the Python script was correctly identifying and highlighting the position of the doors.

[6] The unprocessed data were used as the calculation to determine doorway positions depended on WalkingDirection (the cleaned/processed data contained missing WalkingDirection as they were removed during IQR filtering).

Based on previous studies, 1.5 seconds were subtracted (-1.5 sec) from the start of the window of interest to account for when the participant was approaching the doorway as the aim was to extract the shoulder rotations when the participant was approaching the doorway and while they were beginning to cross it. Specifically, data were extracted from 1.5 seconds before the participant's first shoulder entered the doorway until their first shoulder crossed the doorway. This cutoff was selected because by the time the participant's second shoulder entered the doorway, the shoulder rotation had already occurred. Previous studies have shown that individuals begin rotating their shoulders before crossing narrow apertures and walk sideways through them. The number of collisions with the doors of interest was also computed for later analyses with preprocessed data. See the Python scripts for additional details.

For the current study, only "arrivals" are of interest (i.e., when the participant is approaching/entering the doorway) and not "exits" (i.e., when the participant is leaving/exiting the doorway). Participants walked from Door A to Door B and then from Door B to Door A (see Figure 9 for an illustration). In other words, the doorways of interest are Door B in WalkingDirection 0 (when the participant is approaching Door B) and Door A in WalkingDirection 1 (when the participant is returning towards Door A).

Figure 9 Top-view example of one participant's shoulders and trajectory during the task



Note. The darker red line represents the left shoulder, and the pale green line represents the right shoulder. "A" represents the approximate location of the post with the button in Elevator A and "B" the location of the post with the button in Elevator B.

Step 4: Extract and analyze data

The shoulder rotation angles were then extracted using the Python script "04_shoulder_data_rotation_max_mean.py". This step used cleaned/processed data (i.e., filtered using the IQR method). The Python scripts followed the steps below (see the script for additional details):

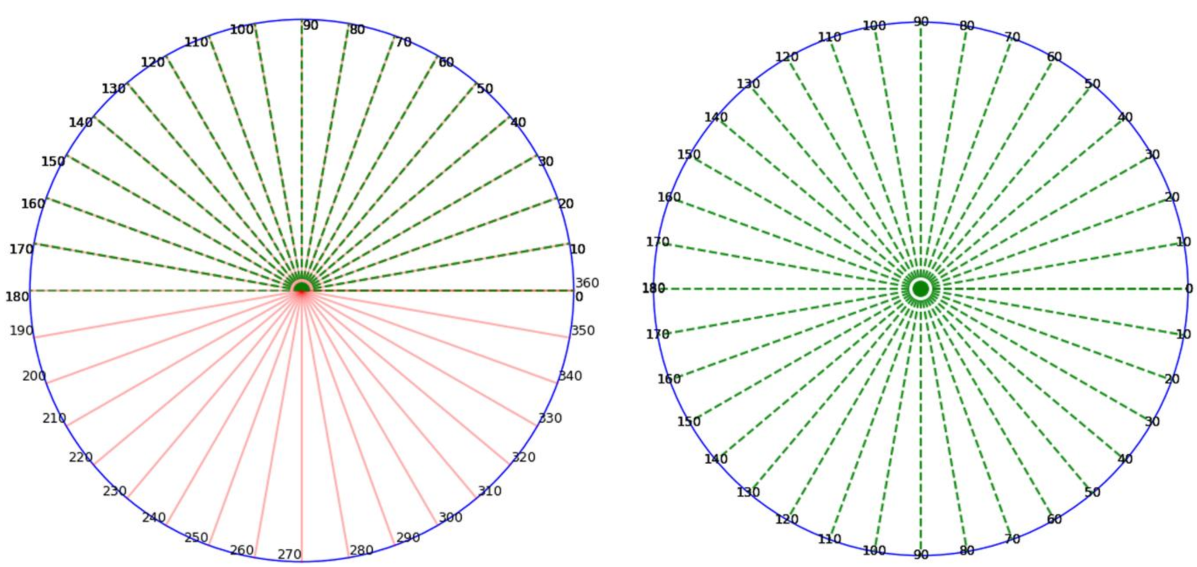
1. Normalize shoulder rotation angles from a range of 0 to 360 degrees into a range of 0 to 180 degrees and flip the angles when the participant is walking in WalkingDirection 1 (see Figure 10 for an illustration).
    a. These transformations were performed to help with the interpretation of the mean shoulder rotation angles (e.g., to avoid computing a mean using 10 degrees and 170 degrees and instead computing the mean using 10 degrees and 10 degrees). Since the aim was to analyze changes in shoulder rotation amplitude as opposed to shoulder rotation direction or orientation, these transformations were considered appropriate for this purpose.
    b. Neither the original data nor the cleaned data contained any negative angles. The original data ranged from 0 to 360 degrees and the cleaned data ranged from 0 to 180 degrees.
2. Identify the maximum shoulder rotation angle for each doorway for each combination of participant (ParticipantID), condition (EVCondition), and walking direction (WalkingDirection).

a. We are interested in areas where the participant is *entering* the elevators and not when they are exiting the elevators: in other words, when participants arrive towards Elevator B in WalkingDirection 0 and arrive towards Elevator A in WalkingDirection 1.

3. Compute the mean shoulder rotation angle for each combination of participant and condition.

    a. Each participant entered/arrived towards each elevator once during each condition. In other words, there were two "arrivals" per condition. The mean shoulder rotation angle of the two "arrivals" was computed for each condition. If a participant had a missing value for either of these points of interest (i.e., Door B in WalkingDirection 0 or Door A in WalkingDirection 1), only the available shoulder rotation angle was used (i.e., a mean value was not computed).

Figure 10 Illustration of rotation angle transformation: (1) Normalize the angles into a range of 0 to 180 degrees (left) and (2) Flip the angles (right)



Descriptive and inferential statistical analyses were performed in SPSS (and not in Python). The mean shoulder rotation angles for each combination of participant and condition were manually inputted in SPSS and compared to observational data (i.e., rotated/did not rotate their shoulders) to confirm whether the two sources of data matched.

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Appendix C

Additional figures and tables

This appendix contains additional figures and tables that did not directly address the study's hypotheses. It is important to note that the results from the point-biserial correlations, independent-samples t-tests, and Mann-Whitney U tests are exploratory, since the unbalanced groups (i.e., Control: 8 versus 15; Risk of falling: 9 versus 15; Risk of falling + Fire: 9 versus 14) could have reduced the statistical power of the tests. Furthermore, the scores on the STAI (anxiety), the SSQ (cybersickness), and some of the ITC-SOPI subscales (presence) do not follow a normal distribution.

Several analyses below were conducted using the SSQ. For correlational analyses specifically exploring the relationship between the SSQ and the STAI, the SSQ was scored using two methods. These methods were recommended by Bouchard et al. (2021), who found a correlation between certain SSQ items and anxiety (STAI). Specifically, raw SSQ scores (i.e., with items related to anxiety) and corrected SSQ scores (i.e., without these items) were calculated. The SSQ items related to anxiety are item 1 (Nausea subscale) and item 9 (Oculomotor subscale). In other words, the corrected Nausea score (SSQ-Nausea-Anx) excludes item 1, the corrected Oculomotor score (SSQ-Oculomotor-Anx) excludes item 9, and the corrected Total score (SSQ-Total-Anx) excludes both items 1 and 9. Each relevant table in the appendix specifies whether the raw or the corrected scores are presented.

Individual characteristics

The sample consisted of 12 women and 13 men. None of the participants had prior experience with VR. Table 6 and Figure 11 presents descriptive statistics of individual characteristics (e.g., age, prior experience with video gaming on PC or console). Table 7 reports correlations between individual characteristics and the main variables of interest (i.e., shoulder rotations, presence, anxiety, and cybersickness). A few correlations were statistically significant. However, most were no longer significant after applying the Holm-Bonferroni correction. Raw SSQ scores (SSQ-Raw) were used to facilitate comparisons between studies.

Table 6 Descriptive statistics of individual characteristics (*n* = 25)

Variable	*M*	*Mdn*	*SD*	Minimum	Maximum
Shoulder width	41.30	39.50	4.67	35.00	52.00
Age	27.92	24.00	10.33	18.00	56.00
ITQ–Total	66.08	65.00	8.66	53.00	84.00
BSQ	16.16	16.00	6.85	8.00	29.00
STAI (Pre)	28.62	27.00	6.86	20.00	48.42
AQ–Anx	24.80	21.00	21.88	.00	83.00

Note. **ITQ** = Immersive Tendencies Questionnaire. **BSQ** = Body Shape Questionnaire. **AQ-Anx** = Acrophobia Questionnaire, Anxiety subscale. Participants completed the questions related to individual characteristics and the ITQ before the first immersion. Participants completed the AQ and the BSQ after the last immersion.

Figure 11 Distribution of prior experience with video gaming on PC or console (*n* = 25)

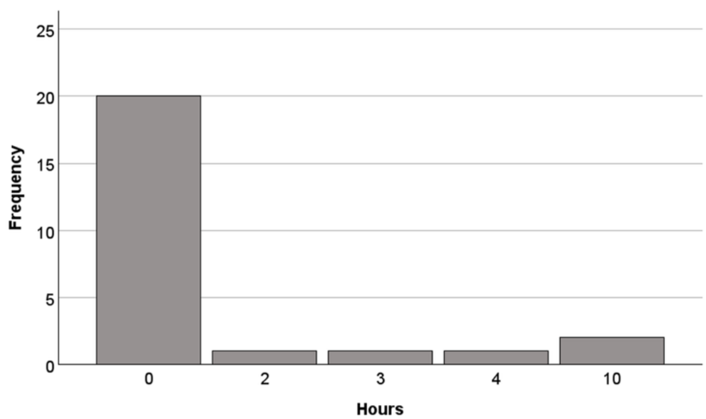


Table 7 Correlations between individual characteristics, shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (SSQ includes items related to anxiety, i.e., items 1 and 9)

Condition and Variable	Shoulder width	Age	ITQ–Total	BSQ	STAI (Pre)	AQ–Anx	Video gaming exp.	Gender
Control								
1. Shoulder Rotation Angle	.14	.32	-.02	-.05	.02	.04	-.36	-.31
2. STAI	-.20	-.14	**-.43***	.26	**.44***	.23	-.36	.08
3. ITC-SOPI–Spatial	-.01	-.04	.25	.30	-.08	**.49***	.41	.17
4. ITC-SOPI–Engagement	-.18	.14	.09	.27	.14	**.43***	.16	.28
5. ITC-SOPI–Naturalness	-.09	.08	.21	.24	-.02	**.63****	.03	.11
6. ITC-SOPI–Neg. Effects	-.11	-.18	-.11	.10	**.43***	.08	-.23	.23
7. SSQ–Nausea-Raw (Post)	-.25	-.28	-.10	.37	.11	.37	-.36	.32
8. SSQ–Oculomotor-Raw (Post)	-.13	-.07	-.37	.00	**.42***	.12	.34	.32
9. SSQ–Total-Raw (Post)	-.20	-.08	-.32	.08	**.46***	.29	.11	.37
Risk of falling								
1. Shoulder Rotation Angle	.05	.31	-.05	-.08	-.10	.06	-.10	-.24
2. STAI	**-.57****	.23	-.16	.38	**.81****	.32	.65	.39
3. ITC-SOPI–Spatial	-.15	-.01	.14	**.40***	.04	**.54****	.05	.33
4. ITC-SOPI–Engagement	-.12	.01	.11	.22	-.13	.11	-.21	.15
5. ITC-SOPI–Naturalness	-.15	-.02	.17	.29	-.16	**.46***	-.05	.28
6. ITC-SOPI–Neg. Effects	**-.42***	-.02	-.08	.22	**.55****	.01	.65	.37
7. SSQ–Nausea-Raw (Post)	–	–	–	–	–	–	–	–
8. SSQ–Oculomotor-Raw (Post)	–	–	–	–	–	–	–	–
9. SSQ–Total-Raw (Post)	–	–	–	–	–	–	–	–
Risk of falling + Fire								
1. Shoulder Rotation Angle	.13	**.45***	-.01	-.34	-.14	-.12	-.21	-.32
2. STAI	**-.60****	.16	-.12	**.50***	**.82****	.37	.34	.34
3. ITC-SOPI–Spatial	-.19	.06	.23	.35	.05	**.50***	-.10	.25
4. ITC-SOPI–Engagement	.02	.22	.21	-.04	-.13	.06	.21	.05
5. ITC-SOPI–Naturalness	-.15	-.03	.08	**.44***	.04	**.67****	-.13	.30
6. ITC-SOPI–Neg. Effects	-.23	-.11	-.27	.12	**.40***	.17	.49	.28

7. SSQ–Nausea-Raw (Post)	–	–	–	–	–	–	–	–
8. SSQ–Oculomotor-Raw (Post)	–	–	–	–	–	–	–	–
9. SSQ–Total-Raw (Post)	–	–	–	–	–	–	–	–

Note. Spearman correlations were performed for all individual characteristics, except gender where point-biserial correlations were conducted. **Control** condition: n = 25 for questionnaires and n = 23 for shoulder rotation angles; **Risk of falling** condition: n = 25 for questionnaires and n = 24 for shoulder rotation angles; **Risk of falling + Fire** condition: n = 25 for questionnaires and n = 23 for shoulder rotation angles. **ITQ** = Immersive Tendencies Questionnaire. **BSQ** = Body Shape Questionnaire. **AQ–Anx** = Acrophobia Questionnaire, Anxiety subscale. Participants completed the questions related to individual characteristics and the ITQ before the first immersion. Participants completed the AQ and the BSQ after the last immersion.* $p < .05$. ** $p < .01$.

Shoulder rotations

Figure 12 shows the distribution of shoulder rotation angles in each experimental condition.

Figure 12 Distribution of participants' shoulder rotation angles in each experimental condition

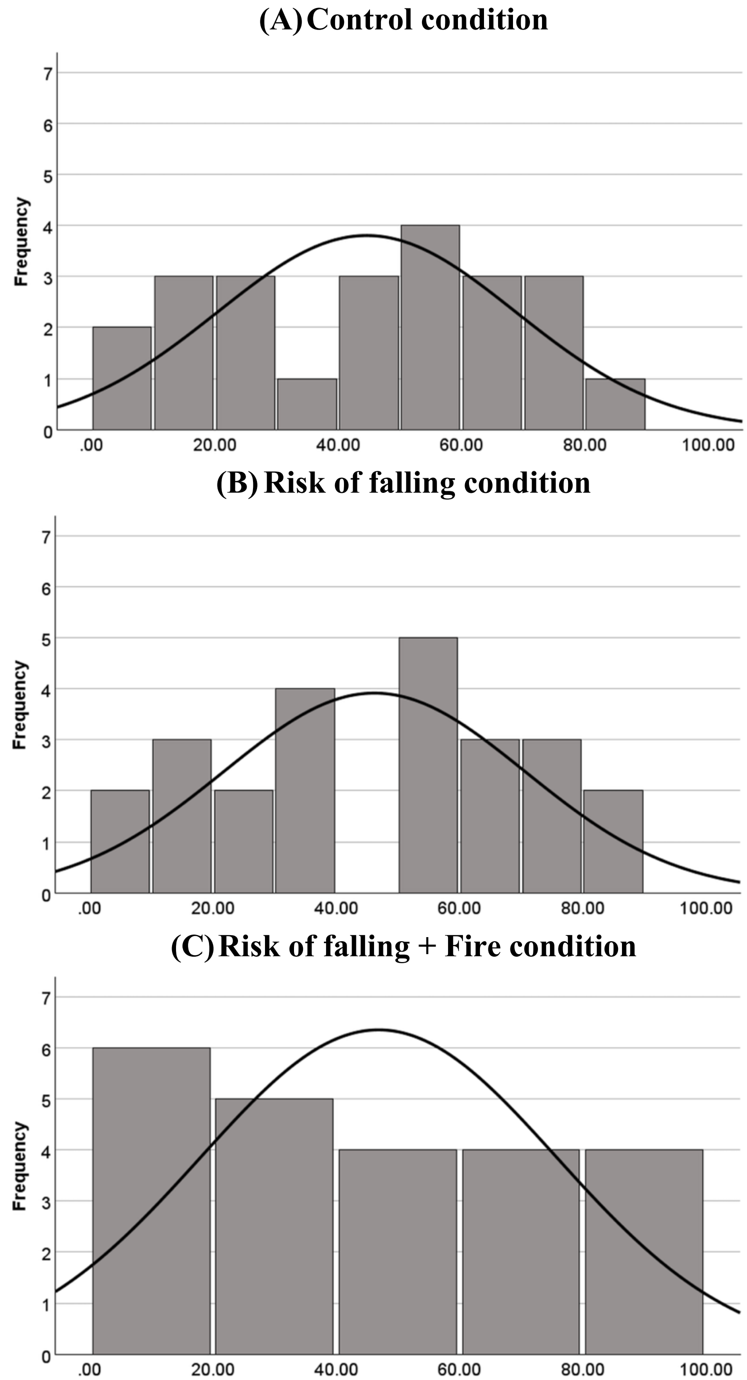
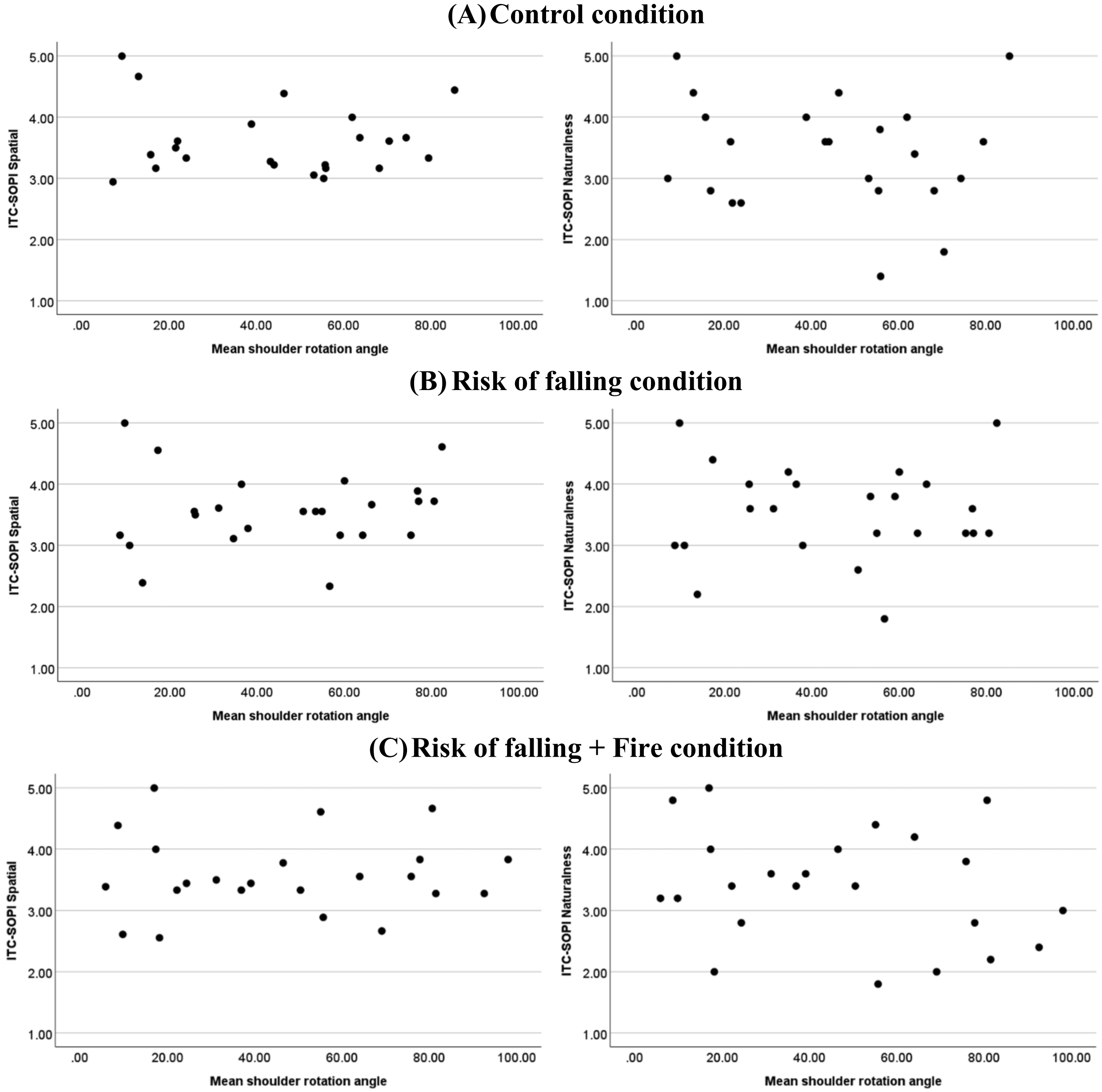


Figure 13 presents scatterplots of shoulder rotation angles and self-report measures of presence within each experimental condition.

Figure 13 Correlations between participants' mean shoulder rotations and ITC-SOPI Spatial Presence and Naturalness subscales in each experimental condition



Exploratory analyses were conducted to examine whether the dichotomous measure of rotating the shoulders would be correlated with the self-report measure of anxiety, presence, or cybersickness. To do so, the participants were first manually classified into two groups: (1) Did not rotate shoulders (coded as 0) for participants with a mean shoulder rotation angle below 35°; and (2) Rotated shoulders (coded as 1) for participants with a mean shoulder rotation angle equal or above 35° (see Table 8 for descriptive statistics). Then, point-biserial correlations (equivalent to Pearson's r) were performed with this new dichotomous variable and the STAI, the ITC-SOPI, and the SSQ-Raw (see Table 9). The correlations did not remain statistically significant after applying the Holm-Bonferroni correction. Moreover, raw SSQ scores (SSQ-Raw) were used to facilitate comparisons between studies.

Table 8 Descriptive statistics of shoulder rotation angles and questionnaire scores for the dichotomous measure of shoulder rotation (Did not rotate shoulders versus Rotated shoulders) per experimental condition

Group and Variable	*M*	*Mdn*	*SD*	Minimum	Maximum
Did not rotate shoulders					
Control (*n* = 8)					
Shoulder Rotation Angle	16.26	16.45	6.12	7.24	23.99
STAI	29.09	24.61	10.18	20.00	49.47
ITC-SOPI–Spatial	3.70	3.44	.73	2.94	5.00
ITC-SOPI–Engagement	3.66	3.62	.73	2.77	4.85
ITC-SOPI–Naturalness	3.50	3.30	.90	2.60	5.00
ITC-SOPI–Neg. Effects	1.75	1.67	.68	1.00	2.67
SSQ–Nausea-Raw (Post)	.75	1.00	.71	.00	2.00
SSQ–Oculomotor-Raw (Post)	1.25	.00	2.19	.00	6.00
SSQ–Total-Raw (Post)	2.00	1.00	2.73	.00	8.00
Risk of falling (*n* = 9)					
Shoulder Rotation Angle	19.76	17.33	9.81	8.66	34.64
STAI	30.26	30.00	9.58	20.00	47.37
ITC-SOPI–Spatial	3.54	3.50	.80	2.39	5.00
ITC-SOPI–Engagement	3.39	3.31	.59	2.46	4.38
ITC-SOPI–Naturalness	3.67	3.60	.85	2.20	5.00
ITC-SOPI–Neg. Effects	1.78	1.50	.80	1.00	3.17
SSQ–Nausea-Raw (Post)	.67	1.00	.71	.00	2.00
SSQ–Oculomotor-Raw (Post)	1.44	.00	2.13	.00	6.00
SSQ–Total-Raw (Post)	2.11	1.00	2.57	.00	8.00
Risk of falling + Fire (*n* = 9)					
Shoulder Rotation Angle	17.23	17.40	8.13	5.91	31.24
STAI	31.78	31.00	8.53	20.00	46.00
ITC-SOPI–Spatial	3.58	3.44	.79	2.56	5.00

ITC-SOPI–Engagement	3.43	3.23	.63	2.69	4.69
ITC-SOPI–Naturalness	3.56	3.40	.94	2.00	5.00
ITC-SOPI–Neg. Effects	1.74	1.50	.74	1.00	2.67
SSQ–Nausea-Raw (Post)	.67	1.00	.71	.00	2.00
SSQ–Oculomotor-Raw (Post)	1.44	.00	2.13	.00	6.00
SSQ–Total-Raw (Post)	2.11	1.00	2.57	.00	8.00
Rotated shoulders					
Control (*n* = 15)					
Shoulder Rotation Angle	59.77	55.93	13.86	38.92	85.42
STAI	26.49	24.00	8.36	20.00	50.00
ITC-SOPI–Spatial	3.54	3.33	.47	3.00	4.44
ITC-SOPI–Engagement	3.63	3.46	.50	3.08	4.85
ITC-SOPI–Naturalness	3.35	3.60	.93	1.40	5.00
ITC-SOPI–Neg. Effects	1.27	1.00	.43	1.00	2.33
SSQ–Nausea-Raw (Post)	.13	.00	.35	.00	1.00
SSQ–Oculomotor-Raw (Post)	1.00	.00	1.69	.00	6.00
SSQ–Total-Raw (Post)	1.13	1.00	1.64	.00	6.00
Risk of falling (*n* = 15)					
Shoulder Rotation Angle	62.09	60.04	14.46	36.46	82.35
STAI	26.47	25.00	7.15	20.00	46.00
ITC-SOPI–Spatial	3.56	3.56	.52	2.33	4.61
ITC-SOPI–Engagement	3.66	3.54	.46	2.92	4.38
ITC-SOPI–Naturalness	3.45	3.20	.75	1.80	5.00
ITC-SOPI–Neg. Effects	1.31	1.00	.42	1.00	2.33
SSQ–Nausea-Raw (Post)	.13	.00	.35	.00	1.00
SSQ–Oculomotor-Raw (Post)	1.00	.00	1.69	.00	6.00
SSQ–Total-Raw (Post)	1.13	1.00	1.64	.00	6.00
Risk of falling + Fire (*n* = 14)					
Shoulder Rotation Angle	65.97	66.59	19.30	36.97	98.02
STAI	27.00	24.50	9.56	20.00	55.00
ITC-SOPI–Spatial	3.58	3.50	.56	2.67	4.67
ITC-SOPI–Engagement	3.66	3.73	.43	2.85	4.23
ITC-SOPI–Naturalness	3.27	3.40	.94	1.80	4.80
ITC-SOPI–Neg. Effects	1.31	1.25	.33	1.00	1.83
SSQ–Nausea-Raw (Post)	.14	.00	.36	.00	1.00
SSQ–Oculomotor-Raw (Post)	1.07	.00	1.73	.00	6.00
SSQ–Total-Raw (Post)	1.21	1.00	1.67	.00	6.00

Table 9 Point-biserial correlations between the dichotomous measure of shoulder rotation (Did not rotate shoulders versus Rotated shoulders), anxiety, presence, and cybersickness

Variable	Control Rotated Shoulders	Risk of falling Rotated Shoulders	Risk of falling + Fire Rotated Shoulders
STAI	-.14	-.23	-.26
ITC-SOPI–Spatial	-.14	.02	.00
ITC-SOPI–Engagement	-.03	.26	.22

ITC-SOPI–Naturalness	-.08	-.14	-.15
ITC-SOPI–Neg. Effects	**-.42***	-.37	-.39
SSQ–Nausea-Raw (Post)	**-.52***	**-.47***	**-.46***
SSQ–Oculomotor-Raw (Post)	-.07	-.12	-.10
SSQ–Total-Raw (Post)	-.20	-.24	-.22

Note. **Control** condition: *n* = 25 for questionnaires and *n* = 23 for shoulder rotation group; **Risk of falling** condition: *n* = 25 for questionnaires and *n* = 24 for shoulder rotation group; **Risk of falling + Fire** condition: *n* = 25 for questionnaires and *n* = 23 for shoulder rotation group.
*$p < .05$.

In addition, independent-samples t-tests and Mann-Whitney U tests were conducted to explore whether the groups (Did not rotate versus Rotated) significantly differed in terms of self-reported anxiety, presence, or cybersickness (see Table 10). The results were no longer statistically significant after applying the Holm-Bonferroni correction.

Table 10 Results from independent-samples t-tests (two-sided *p*, equal variances assumed) and Mann-Whitney U tests per experimental condition

Variable	Control			Risk of falling			Risk of falling + Fire		
	t	*df*	*p*	*t*	*df*	*p*	*t*	*df*	*p*
STAI	.66	21	.517	1.11	22	.279	1.22	21	.237
ITC-SOPI–Spatial	.65	21	.526	-.07	22	.942	.02	21	.986
ITC-SOPI–Engagement	.15	21	.884	-1.24	22	.227	-1.05	21	.307
ITC-SOPI–Naturalness	.38	21	.707	.64	22	.526	.71	21	.487
ITC-SOPI–Neg. Effects	2.10	21	**.048***	1.88	22	.073	1.92	21	.068
SSQ–Nausea-Raw (Post)	2.82	21	**.010****	2.48	22	**.021***	2.35	21	**.029***
SSQ–Oculomotor-Raw (Post)	.31	21	.763	.57	22	.577	.46	21	.649
SSQ–Total-Raw (Post)	.96	21	.349	1.14	22	.265	1.02	21	.320

	Control		Risk of falling		Risk of falling + Fire	
	U	*p*	*U*	*p*	*U*	*p*
STAI	54.00	.697	52.00	.351	38.50	.120
ITC-SOPI–Spatial	55.00	.746	54.00	.419	62.50	.975
ITC-SOPI–Engagement	56.50	.821	48.00	.244	43.00	.207
ITC-SOPI–Naturalness	59.50	.974	58.00	.568	54.50	.591
ITC-SOPI–Neg. Effects	34.00	.079	41.50	.107	46.00	.272
SSQ–Nausea-Raw (Post)	29.50	**.014***	38.00	**.027***	36.00	**.034***
SSQ–Oculomotor-Raw (Post)	59.50	.971	61.00	.664	58.50	.754
SSQ–Total-Raw (Post)	48.00	.414	49.50	.261	48.50	.340

Note. **Control** condition: *n* = 8 did not rotate shoulders and *n* = 15 rotated shoulders; **Risk of falling** condition: *n* = 9 did not rotate shoulders and *n* = 15 rotated shoulders; **Risk of falling + Fire** condition: *n* = 9 did not rotate shoulders and *n* = 14 rotated shoulders.
*$p < .05$. **$p < .01$.

Cybersickness

Spearman correlations were performed between anxiety (STAI), presence (ITC-SOPI), cybersickness (SSQ and ITC-SOPI–Negative Effects), and shoulder rotation angles. Table 11 reports the descriptive statistics with the corrected SSQ scores (SSQ-Anx). Table 12 contains Spearman correlations with the raw SSQ scores (SSQ-Raw). Table 13 reports Spearman correlations with the corrected SSQ scores (SSQ-Anx). Many of the correlations were no longer statistically significant after applying the Holm-Bonferroni correction.

Table 11 Descriptive statistics of corrected SSQ scores per experimental condition (n = 25)

Variable	Pre			Post		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*
SSQ–Nausea-Anx	.20	.00	.50	.20	.00	.50
SSQ–Oculomotor-Anx	.76	1.00	.83	1.24	.00	1.98
SSQ–Total-Anx	.96	1.00	1.02	1.44	1.00	2.12

Note. Participants completed the SSQ before the first immersion and after the last immersion.

Table 12 Spearman correlations between shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (SSQ includes items related to anxiety, i.e., items 1 and 9)

Condition and Variable	SSQ Nausea-Raw Pre	SSQ Oculomotor-Raw Pre	SSQ Total-Raw Pre	SSQ Nausea-Raw Post	SSQ Oculomotor-Raw Post	SSQ Total-Raw Post
Control						
1. Shoulder Rotation Angle	-.15	.17	.09	-.31	.04	-.05
2. STAI	.31	.25	.37	.24	.32	.38
3. ITC-SOPI–Spatial	-.17	-.07	-.13	**.43***	-.39	-.12
4. ITC-SOPI–Engagement	-.11	.13	.10	.34	-.15	.03
5. ITC-SOPI–Naturalness	-.08	-.08	-.10	.27	-.32	-.15
6. ITC-SOPI–Neg. Effects	.31	.30	**.41***	.34	.35	**.43***
Risk of falling						
1. Shoulder Rotation Angle	-.11	.02	-.01	-.27	-.10	-.16
2. STAI	**.45***	**.46***	**.55****	.29	**.40***	**.51****
3. ITC-SOPI–Spatial	-.07	-.10	-.15	.34	-.39	-.15
4. ITC-SOPI–Engagement	-.38	-.12	-.23	.02	**-.40***	**-.41***
5. ITC-SOPI–Naturalness	-.12	-.22	-.26	**.40***	**-.57****	-.34
6. ITC-SOPI–Neg. Effects	.15	**.44***	**.48***	.10	**.57****	**.49***
Risk of falling + Fire						
1. Shoulder Rotation Angle	-.12	.06	.02	-.35	-.05	-.15
2. STAI	**.41***	**.46***	**.55****	**.41***	.34	**.50***
3. ITC-SOPI–Spatial	-.13	-.08	-.12	.23	**-.42***	-.22
4. ITC-SOPI–Engagement	-.35	-.03	-.10	-.14	-.25	-.28
5. ITC-SOPI–Naturalness	-.13	-.12	-.16	.36	-.34	-.14
6. ITC-SOPI–Neg. Effects	.18	.27	.34	.13	**.45***	**.40***

Note. **Control** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles; **Risk of falling** condition: $n = 25$ for questionnaires and $n = 24$ for shoulder rotation angles; **Risk of falling + Fire** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles.
$^{*}p < .05$. $^{**}p < .01$.

Table 13 Spearman correlations between shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (SSQ excludes items related to anxiety, i.e., items 1 and 9)

Condition and Variable	SSQ Nausea-Anx Pre	SSQ Oculomotor-Anx Pre	SSQ Total-Anx Pre	SSQ Nausea-Anx Post	SSQ Oculomotor-Anx Post	SSQ Total-Anx Post
Control						
1. Shoulder Rotation Angle	-.23	.17	.08	-.28	.02	-.07
2. STAI	.38	.24	.32	.13	.32	.34
3. ITC-SOPI–Spatial	-.07	-.06	-.12	.34	**-.40***	-.26
4. ITC-SOPI–Engagement	-.09	.17	.10	.25	-.17	-.11
5. ITC-SOPI–Naturalness	.09	-.01	-.03	.13	-.34	-.29
6. ITC-SOPI–Neg. Effects	**.43***	.38	**.47***	.29	.34	**.41***
Risk of falling						
1. Shoulder Rotation Angle	-.15	.12	.05	-.23	-.11	-.18
2. STAI	.39	**.48***	**.53****	.13	**.40***	**.43***
3. ITC-SOPI–Spatial	-.08	.03	-.03	.24	-.39	-.27
4. ITC-SOPI–Engagement	-.37	-.02	-.17	.02	-.38	**-.41***
5. ITC-SOPI–Naturalness	-.08	-.05	-.11	.29	**-.58****	**-.47***
6. ITC-SOPI–Neg. Effects	.11	**.48***	**.46***	.08	**.57****	**.52****
Risk of falling + Fire						
1. Shoulder Rotation Angle	-.18	.15	.08	-.23	-.06	-.13
2. STAI	.39	**.46***	**.52****	.21	.34	.38
3. ITC-SOPI–Spatial	-.01	.02	-.04	.16	**-.43***	-.34
4. ITC-SOPI–Engagement	-.23	-.03	-.14	-.02	-.26	-.28
5. ITC-SOPI–Naturalness	.04	-.06	-.09	.19	-.34	-.26
6. ITC-SOPI–Neg. Effects	.17	.38	.39	.21	**.45***	**.48***

Note. **Control** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles; **Risk of falling** condition: $n = 25$ for questionnaires and $n = 24$ for shoulder rotation angles; **Risk of falling + Fire** condition: $n = 25$ for questionnaires and $n = 23$ for shoulder rotation angles.
*$p < .05$. **$p < .01$.

Chapitre 5 : Exploring the Relationship Between Presence, Anxiety, and Cybersickness in a Virtual Environment Involving Heights

(Article 3)

Exploring the relationship between presence, anxiety, and cybersickness in a virtual environment involving heights

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Acknowledgements

The authors wish to thank Marie-Christine, Paul, Maxence, Mathilde, and Simon for developing the virtual environments used in the study. The authors also thank the participants who took part in the study. Finally, the authors would like to thank Anne and Meghan for supporting data collection.

Funding

The following funding agencies provided financial support for the research infrastructure and development of the virtual environment: Canada Research Chairs (#210762, 231039) and Canada Foundation for Innovation (#11138).

Conflict of interest

SB is president and owner of Cliniques et Développement In Virtuo, a spin-off company from his university that distributes virtual environments. The terms and arrangements for this spin-off have been reviewed and approved by the Université du Québec en Outaouais in accordance with its Conflict of Interest policies. He also receives honoraria from conferences, workshops, and books. The remaining authors have no relevant financial or non-financial interests to disclose.

Data availability

The data that supports the findings of this study is available upon request addressed directly to the relevant Research Ethics Boards (comite.ethique@uqo.ca and ethique@uottawa.ca). The datasets are not publicly available due to privacy and ethical restrictions.

Highlights

- Virtual sliding doors used to behaviorally assess presence in anxiety-inducing virtual environment.
- No significant correlation between self-reported and behavioral presence.
- Significant correlation between self-reported anxiety and cybersickness.
- Virtual reality studies should consider using both self-report and behavioral measures, as they may not necessarily be concordant.
- Evaluations of anxiety-related applications should distinguish more clearly anxiety and cybersickness.

Abstract

Presence in virtual reality is commonly assessed using self-report measures, but these often measure presence retrospectively. A previous study evaluated a behavioral measure of presence, which involved participants physically rotating their shoulders to cross narrow virtual sliding doors. During the immersions, participants physically walked on a virtual wooden plank (with a matching counterpart in the laboratory). Two experimental conditions included a deep virtual pit to induce anxiety. The results showed a non-significant correlation between the self-report and behavioral measures of presence, as well as between presence and anxiety. However, there was a statistically significant correlation between anxiety and cybersickness. Building on the previous study, the current study aimed to assess whether changes made to the virtual environment and the study protocol influenced the relationship between the self-report and behavioral measures of presence. The study also examined the relationship between presence, anxiety, and cybersickness. Twenty-seven participants were exposed to two conditions (randomized order): (1) Risk of falling condition (deep virtual pit) and (2) Control condition (no experimental manipulation). Participants completed a postural stability test and questionnaires before and after the immersions. Most correlations were not statistically significant, except for the one between cybersickness and anxiety. The results replicate previous findings, which suggest that subjective and behavioral measures of presence may show a pattern of discordance also found with other concepts. They also suggest that evaluations of anxiety-related virtual reality applications could benefit from using methods to distinguish between anxiety and cybersickness. Future research is needed to further evaluate the relationship between self-report and behavioral measures of presence, as well as between cybersickness and postural stability.
Keywords: Anxiety, Presence, Cybersickness, Virtual reality, Postural stability

1. Introduction

Over the past decades, the use of virtual reality (VR) has increased in several fields, such as psychotherapy (Wiederhold & Bouchard, 2014), education (Lampropoulos & Kinshuk, 2024), and training (Leite & Vieira, 2025). One key component of user experience in VR is presence, which refers to the subjective feeling of “being there” in the virtual environment (Heeter, 1992). Slater et al. (2009, 2010, 2018, 2022) divided presence into two components: (1) place illusion and (2) plausibility illusion. Slater defines the place illusion as the feeling of being transported elsewhere, also referred to as presence or spatial presence. Plausibility illusion refers to the feeling of realness of the virtual environment. These illusions influence user behavior in VR (Berthiaume et al., 2018): when users feel like they “are there” in the virtual environment and like events within it are actually occurring, they are more likely to behave realistically. For example, if an individual is walking on an elevated narrow plank in VR, and they feel like they are actually at heights (place illusion) and like they are actually walking on the plank (plausibility illusion), they will likely behave as they would in the physical environment (e.g., higher self-reported anxiety, more cautious behavior). For many applications (e.g., safety training for working at heights, VR-based exposure treatment for fear of heights), it is important that individuals behave realistically in VR, as it is expected that their behavior will generalize from the physical environment to VR and vice versa.

Many factors have an impact on presence. Two factors examined in previous studies include multisensory stimulation and anxiety. Several studies have shown that multisensory stimulation, such as haptic feedback and olfactory stimuli, can enhance presence (e.g., Baus & Bouchard, 2017; Ribé-Viñes et al., 2025; Turchet et al., 2012). Moreover, studies revealed a positive correlation between anxiety and presence, where higher anxiety led to increased presence (e.g., Brübach et al., 2025; Bouchard et al., 2008; Gromer et al., 2019; Maymon et al., 2024; Robillard et al., 2003). However, some studies found a negative correlation between presence and anxiety (e.g., Ling et al., 2012; Villani et al., 2012). For a review of the relationship between the two variables, see the meta-analysis by Ling et al. (2014). Given that anxiety is commonly elicited in VR applications (e.g., clinical applications, Wiederhold & Bouchard, 2014; construction safety, Cordeiro et al., 2025; Simeonov et al., 2011), it is important to better understand its impact on presence and behavior in the virtual environment, as it is expected that participants' behavior in VR will be similar to the physical environment. Several previous studies have used virtual environments to simulate heights to induce anxiety (e.g., Gromer et al., 2019; Kisker et al., 2021).

Presence is commonly assessed using self-report measures, such as questionnaires (e.g., Bouchard et al., 2008; Gromer et al., 2019; Kisker et al., 2021). However, physiological measures (e.g., heart rate, skin conductance) and behavioral measures have also been used (e.g., Athif et al., 2020; Saha et al., 2025). Few studies have used multiple measures of presence, particularly physiological and behavioral measures (two recent studies by Maymon et al., 2024 are one exception). To the authors' knowledge, currently, there are few physiological or behavioral measures of presence that have been shown to be correlated with self-reported presence and replicated in other studies (e.g., heart rate; Higuera-Trujillo et al., 2017; Meehan et al., 2002; Wiederhold et al., 2001).

One limitation of self-report measures is that they often assess presence retrospectively rather than during immersions. Breaks in presence (BIPs) have also been used to evaluate presence during immersions, where users will report (often verbally or by using a cursor) when they do not feel present in the virtual environment (e.g., Brogni et al., 2003; Slater & Steed, 2000). However, BIPs also rely on self-report. Measures such as BIPs and behavioral measures allow to assess presence continuously during immersions.

Behavioral measures assume that if users feel present in the virtual environment, their responses to a situation or an object in the virtual environment should closely resemble their responses in the physical environment (Mestre, 2015). In two studies, Lepecq et al. (2009) and Mestre et al. (2016) showed that participants physically rotated their shoulders to cross narrow apertures in VR, with average critical aperture to shoulder (A/S) ratios between 1.2 and 1.4. Berthiaume et al. (submitted) used a relatively similar methodology, but they also exposed participants to anxiety-inducing scenarios. Specifically, during the immersions, participants physically walked on a virtual plank (with a matching counterpart in the laboratory) and crossed narrow virtual sliding doors. In two conditions, participants were exposed to a deep virtual pit, with one condition also containing a virtual fire. The results indicated that the self-report and the behavioral measures of presence were not significantly correlated. This unexpected finding may be explained by several reasons, including the phenomena known as discordance between subjective and behavioral measures (e.g., Benoit Allen et al., 2015; Craske & Craig, 1984; Hodgson & Rachman, 1974; Rachman & Hodgson, 1974).

Moreover, Berthiaume et al. (submitted) did not find a statistically significant correlation between presence and anxiety. However, the correlation between anxiety and cybersickness was statistically significant. While the correlation between self-reported presence and the amplitude of shoulder rotation was not significantly correlated in Berthiaume et al. (submitted), Hackney et al. (2015) found that the magnitude of shoulder rotations was smaller when crossing a narrow aperture in the condition at heights than in the condition on the ground in the physical environment. This suggests that heights can affect shoulder rotations. These studies inspired the current study's objectives and improved methodology.

Cybersickness

Cybersickness, another component of user experience in VR, is defined as unwanted negative symptoms that users can experience during or after an immersion, such as nausea, headache, dizziness, etc. (Stone III, 2017). While VR headsets have improved over the past years, cybersickness remains an important challenge for applications in several domains (Yildirim, 2020). Previous studies have investigated the relationship between cybersickness and presence, as well as between cybersickness and anxiety. Some studies have found a positive correlation between cybersickness and presence (e.g., Liu & Uang, 2011; Liu & Uang, 2011), but others observed a negative (e.g., Usoh et al., 1999; Weech et al., 2020) or a non-significant correlation (e.g., Kooijman et al., 2022; Servotte et al., 2020). For a more detailed discussion, see the review by Weech et al. (2019).

Previous studies have shown that cybersickness and anxiety have overlapping physical symptoms (e.g., general discomfort, difficulty concentrating) and can both impact postural stability (e.g., Litleskare, 2021; Cleworth et al., 2012; Wang et al., 2024). As such, it can be difficult to distinguish between both conditions. Recently, Berthiaume et al. (submitted) reported a significant correlation between anxiety and cybersickness. Several studies have shown that their symptoms can be conflated (e.g., Bouchard et al., 2007; Bouchard et al., 2009; Bouchard et al., 2021; Ling et al., 2011; Quintana et al., 2014). Consequently, Bouchard et al. (2021) suggested calculating two separate sets of scores when using the Simulator Sickness Questionnaire (SSQ, Kennedy et al., 1993), a commonly used questionnaire to assess cybersickness: one set of scores with items related to anxiety (“Raw” scores) and a second set without these items (“Anx” scores).

The postural instability theory of motion sickness (Riccio & Stoffregen, 1991; Smart et al., 2002; Stoffregen, 2011; Stoffregen & Smart, 1998) hypothesizes that postural instability should precede the onset of symptoms of cybersickness. In other words, users’ postural stability prior to exposure to potentially nauseogenic stimuli would differ between users who subsequently experience cybersickness and those who do not (e.g., Bailey et al., 2022). Moreover, motion sickness history has been shown to contribute to cybersickness (Rebenitsch & Owen, 2014). Previous studies have assessed postural stability and analyzed center of pressure (COP) parameters, such as ellipse area/surface, path length, velocity, etc. (see Paillard & Noé, 2015 for a list of COP parameters). However, studies assessing the relationship between cybersickness and postural stability indicated mixed results (e.g., Arcioni et al., 2019; Litleskare, 2021), which suggests that it is a complex relationship, and further research is needed to explore whether postural stability is an adequate measure and predictor of cybersickness. A better understanding of measures and predictors of cybersickness could help develop more personalized virtual environments and improve user comfort. In short, the use of a combination of measures would provide a more comprehensive perspective.

Objectives and hypotheses

Based on the results of the previous study (Berthiaume et al., submitted), the current study examined, with an improved methodology, the relationship between self-report and behavioral measures of presence. For instance, the current methodology incorporated changes to the study protocol and the virtual environment to increase presence (e.g., including haptic feedback) and anxiety (e.g., removing wooden beams around the plank). Narrow aperture crossing was selected as the behavioral measure of presence because it has practical applications, such as better understanding navigation in narrow workspaces at heights on construction sites (e.g., Habibnezhad et al., 2019). Moreover, while previous studies exposed participants to virtual heights and administered questionnaires on presence and cybersickness (e.g., Gromer et al., 2018; Robillard et al., 2003), they did not directly examine the relationship between presence, cybersickness, and anxiety. As such, the current study also further explored the relationship between these variables.

Based on the literature review, and despite the results from a previous study (Berthiaume et al., submitted), the following hypotheses were put forward:

1- The behavioral indicator of presence will be significantly positively correlated with self-reported presence (i.e., a larger amplitude of shoulder rotations would correspond to higher self-reported presence).

2- Self-reported presence and anxiety will be significantly higher in the condition with the risk of falling than the control condition.

3- Self-reported presence, anxiety, cybersickness within each experimental condition will be significantly positively correlated.

In addition, exploratory analyses investigated whether self-reported cybersickness after the immersions was related to postural stability and self-reported motion sickness before the first immersion (pre-immersion). Exploratory analyses also examined the relationship between anxiety and postural stability within each experimental condition.

2. Methods

The study was approved by the Research Ethics Boards of the Université du Québec en Outaouais (#2021-1359) and the University of Ottawa (#H-03-21-6772). All participants provided their written consent prior to taking part in the study.

Participants

The inclusion and exclusion criteria for the study were identical to Berthiaume et al. (submitted). Specifically, potential participants who met any of the following criteria were excluded during recruitment: having a medical or psychological condition for which VR is not recommended (migraines; epilepsy; cardiac, vestibular, or important ocular conditions; frequent discomfort or motion sickness while travelling; psychotic disorder or schizophrenia; substance abuse) or having a phobia of fire or heights. The exclusion criteria led to one exclusion during recruitment due to severe height phobia. A convenience sample of 37 participants took part in the study. Twelve participants were excluded from the analyses due to technical issues ($n = 6$), poor stereoscopic vision ($n = 5$), and withdrawing consent during the debriefing ($n = 1$). The final sample included 25 participants (15 women and 10 men). The sample's mean age was 21.96 ($SD = 3.74$; range from 18 to 32). None of the participants took part in the study conducted by Berthiaume et al. (submitted).

VR equipment

Data collection took place at the Cyberpsychology Laboratory of the Université du Québec en Outaouais. The VR equipment included a wireless VIVE Pro head-mounted display, two VIVE hand controllers, four VIVE Trackers 2018 (two for shoulders and two for feet), and four SteamVR Base Stations 2.0 (see Berthiaume et al., submitted for the layout of the room). The two shoulder trackers were placed on a custom-made pack frame (i.e., a rigid metal frame).

A Tactosy for Arms by bHaptics (https://www.bhaptics.com/support/downloads/?type=manual) was attached to each pack frame strap (see Figure 1) and delivered haptic feedback (i.e., vibrated) when participants collided with the virtual doors. The pack frame with the two shoulder trackers and the haptic feedback devices weighed 4.11 pounds (1.86 kilograms). The experimenter controlled the settings for the virtual environments on a desktop computer that ran Windows 11 Enterprise (Intel® Core™ i9-11900K CPU @ 3.40GHz, 32 GB RAM, 64-bit operating system) with an NVIDIA GeForce RTX 3080 graphics card (version 566.14). For a full description of the VR equipment, see Berthiaume et al. (submitted).

Figure 1 Photo of the devices over the shoulders on the pack frame that delivered haptic feedback (left) and of a participant wearing the virtual reality equipment (right)

Note. Photo on the right: The shoulder trackers (on the pack frame) are circled in white (dotted line). In the white box (dashed line) is one of the devices that delivered haptic feedback (the device over right shoulder is not visible in the photo). The foot trackers (around the ankles) are circled in grey (solid line).

Virtual environments

The virtual environments were developed using the Unity 3D game engine version 2021.3.6f1 (Unity, 2021) and run via the application SteamVR developed by Valve Corporation (version 2.8.8; https://www.steamvr.com/en/). The virtual environments represented a construction site in a downtown area. For additional screenshots of the virtual environments, see Berthiaume et al. (submitted).

Practice environment

A practice environment (see Figure 2) was used to familiarize participants with the VR equipment and the task to complete in the virtual environment. This environment consisted of a 2-minute walk on a virtual wooden plank (approximately 30 cm in width; 7 m in length) on the ground floor of a virtual skyscraper under construction. As such, the practice environment did not provide the impression of being at a height. The plank was used in all experimental conditions. Participants were asked to physically walk on the virtual wooden plank and press virtual buttons at opposite ends of the plank using the hand controllers (see Procedure for additional details). Participants walked on a plank of identical dimensions in the physical environment and that the virtual button (appearance and position) was identical in all virtual environments. During both the practice trial and the experimental trials, participants walked without shoes and in their socks on a physical plank of identical dimensions to provide haptic feedback and increase the realism of the scenario. Wooden beams were placed on each side of the plank in the practice environment to familiarize participants with the haptic feedback; when participants collided with the beams, the sensors on the pack frame vibrated.

Figure 2 Screenshot of the virtual environment for the Practice Trial

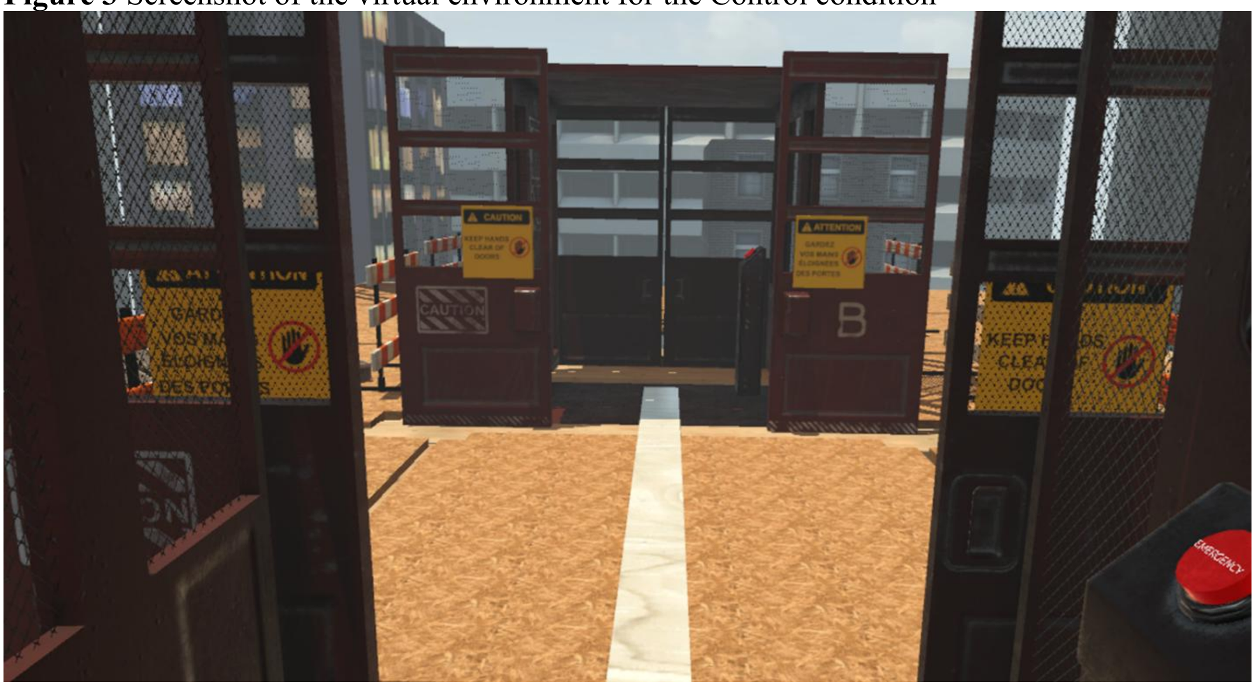
Note. This virtual environment was used to familiarize participants with the VR equipment and the virtual environment. When participants pressed the button, it turned from red to green.

Main environment

The immersions for the experimental conditions took place in the Main environment, on the eighth floor of the virtual skyscraper under construction (virtual height of 35 m from the virtual ground floor based on Wuehr et al., 2019). The entire building was made of wood. On the floor where participants were located, there were two elevators, which could open and close to a narrower width. When the doors were fully open, the aperture width was 250 cm. When the doors were closed to a narrower width, the aperture width varied according to participants' physical shoulder width (i.e., the width of participants' virtual shoulders corresponded to the width of their physical shoulders, not the width of the pack frame). Specifically, based on the studies by Lepecq et al.'s (2009) and Mestre et al.'s (2016), the current study used an aperture to shoulder ratio of 0.82 (i.e., aperture width narrower than participants' shoulders). This ratio was selected to ensure that all participants physically rotated their shoulders. In other words, the aperture width was larger for participants with wider shoulders than for participants with narrower shoulders.

Control condition: The virtual environment for the Control condition was identical to the previous study (Berthiaume et al., submitted), except that a warning sign was placed on each of the virtual elevator doors instructing participants to keep their hands clear of the doors (see Figure 3). In addition, if participants collided with the elevator doors, the devices over their shoulders vibrated (see Figure 1).

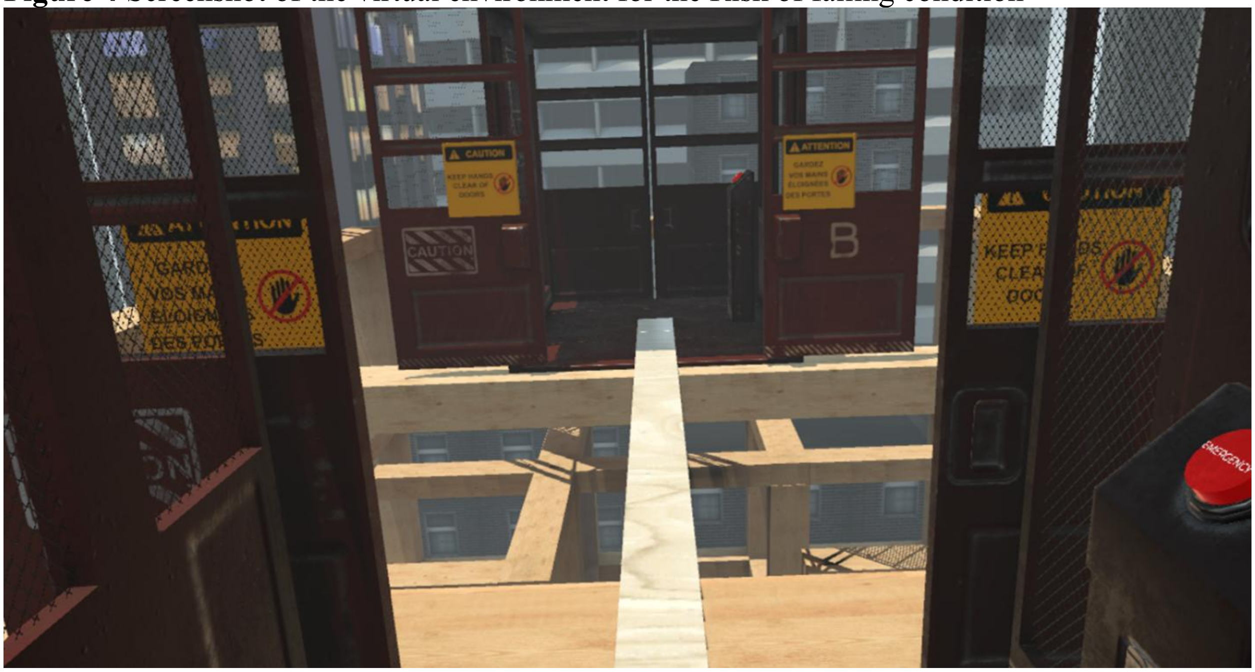
Figure 3 Screenshot of the virtual environment for the Control condition



Risk of falling condition: In this condition, the virtual floor surrounding the plank was removed to induce anxiety. The virtual environment for the Risk of falling condition (see Figure 4) was also identical to the previous study (Berthiaume et al., submitted), except that a warning sign was placed on each of the virtual elevator doors to encourage participants not to touch the doors (see Figure 4). Furthermore, lower floors were removed to intensify the feeling of height.

If participants looked down, they could see virtual feet and a deep pit. If participants' shoulders collided with the elevator doors, the trackers over their shoulders vibrated (see Figure 1).

Figure 4 Screenshot of the virtual environment for the Risk of falling condition



Measures

Participants completed several questionnaires and behavioral measures before, during, and immediately after the immersions in VR. The questionnaires were selected for their demonstrated reliability and validity. Francophone participants completed a French version of the questionnaires. Participants completed all questionnaires through LimeSurvey on a separate laptop. For a full description of the measures used, see Berthiaume et al. (submitted). The current study did not use physiological measures due to suspected Bluetooth interference with the devices that delivered haptic feedback.

Prior to the immersions, participants completed a sociodemographic and a health questionnaire, the State scale from the State-Trait Anxiety Inventory (STAI: 20 items rated on 4-

point Likert scale; Spielberger et al., 1983), the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ: 18 items rated on a 4-point Likert scale; Golding, 1998, 2006), the Simulator Sickness Questionnaire (SSQ: 16 items rated on a 4-point Likert scale; Kennedy et al., 1993), and the Immersive Tendencies Questionnaire (ITQ: 18 items rated on a 8-point Likert scale; Witmer & Singer, 1998). Additional details on the MSSQ are provided below as this questionnaire was not used during the previous study (Berthiaume et al., submitted). Participants also completed a postural stability test using force plates (see below for additional details).

During the immersions, the virtual sliding doors developed by Lepecq et al. (2009) and Mestre et al. (2016) were used to evaluate presence, which was quantified by the amplitude (in degrees) with which participants rotated their shoulders to pass through narrow virtual doors. The VR application used in the current study logged shoulder rotations in degrees and recorded in an output file whether the participant collided with the virtual doors or not. Shoulder rotations were logged 20 times per second.

Following each immersion, participants completed the ITC-Sense of Presence Inventory (ITC-SOPI: 44 items rated on a 5-point Likert scale; Lessiter et al., 2001), the State scale from the STAI (Spielberger et al., 1983), and the SSQ (Kennedy et al., 1993). Participants also completed the postural stability test (see below for additional details).

Motion Sickness Susceptibility Questionnaire Short-form: This questionnaire was developed by Golding (1998, 2006) based on the “Reason and Brand MSSQ” (Reason, 1968; Reason & Brand, 1975). The MSSQ-Short is divided into two sections: (1) Experience during childhood (before age 12) and (2) Experience over the last 10 years. Both sections ask respondents how sick or nauseated they felt in various situations: cars, buses or coaches, trains, aircraft, small boats, ships, swings in playgrounds, roundabouts in playgrounds, and funfair rides.

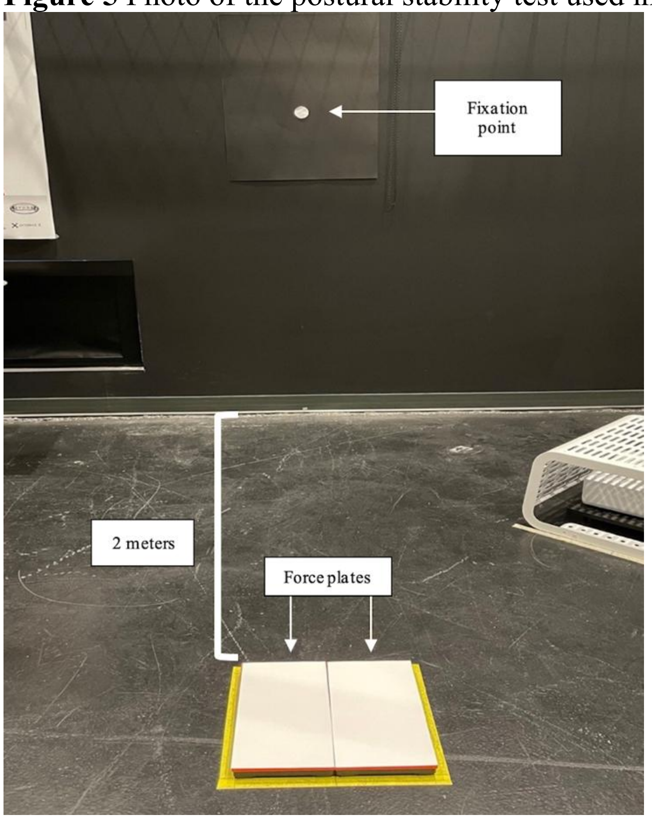
Each situation is rated on a 4-point Likert scale from "*Never felt sick*" (0) to "*Frequently felt sick*" (3) and includes the option "*Not applicable – Never travelled*". The questionnaire has good reliability (α = 0.87) and test-retest reliability (r = 0.9). Gardé (2018) and Paillard et al. (2013) translated the questionnaire to French. Participants completed the MSSQ-Short prior to the first immersion. The MSSQ-Short was scored using the procedure outlined in Golding (1998).

Postural stability test: The experimenter administered a static force plate-based Romberg test (quiet standing) prior to the first immersion and following each immersion (see Figure 5). Two individual portable K-Force plates by Kinvent Physio (similar to https://kinvent.com/kinvent-product/portable-force-plates/) were positioned directly on the floor (i.e., firm surface), side-by-side, 2 meters from the wall. The force plates were automatically recalibrated before each measurement and had an acquisition frequency of up to 75 Hz. A fixation point (5 cm in diameter) was affixed to the wall at the participant's eye level. A blank sheet of paper was placed on each force plate for the experimenter to trace participants' feet to ensure consistent foot placement. Participants completed the test without their shoes (in their socks). During the test, participants stood in a comfortable position (feet spread at approximately hip width) with one foot centered on each force plate. The experimenter asked participants to stand straight and as still as possible with their arms by their side and their shoulders relaxed.[1] The test comprised two trials of 25 seconds each, in the following order: (1) eyes open (participants were asked to look at the fixation point) and (2) eyes closed (participants were asked to briefly look at the fixation point and then to close their eyes), see Appendix A for instructions to participants. The SmartPredict application developed by IDP Santé (https://play.google.com/store/apps/details?id=com.nelumbo.develop.idp) ran the postural

[1] The experimenter visually confirmed that participants were standing in the correct position and looking at the fixation point (trial with eyes open) or had their eyes closed (trial with eyes closed) prior to beginning the trial.

stability test and automatically calculated center of pressure (COP) parameters. The following COP parameters for each immersion were extracted from the application for further analysis: (1) 95% confidence ellipse (sway) area (mm^2); and (2) mean COP velocity (mm/s). The 95% confidence ellipse area refers to the area that contains 95% of the COP trajectory in the medial-lateral (ML) and anterior-posterior (AP) direction during the trial (a smaller ellipse/surface represents better stability, Paillard & Noé, 2015). The mean COP velocity indicates the average speed of COP movement during the trial (a lower velocity signifies better postural control, Asseman et al., 2004) and has been considered more reliable across trials than other COP parameters (Cornilleau-Pérès et al., 2005; Duarte & Freitas, 2010; Paillard & Noé, 2015).

Figure 5 Photo of the postural stability test used in the study



Procedure

The University of Ottawa's Integrated System of Participation in Research was used to recruit participants (https://www.uottawa.ca/research-innovation/inspire/discover-lab/ispr-student-pool). Participants were first screened via telephone to confirm their eligibility. They were then invited to the Cyberpsychology Laboratory at the Université du Québec en Outaouais to take part in the study.

The experimenter first welcomed participants, then briefly explained the study, and responded to any questions. Participants then read and signed a consent form. Only a partial objective was disclosed to avoid biasing participants' behavior. Specifically, the consent form indicated that the study examined presence in VR, or the feeling of "being there" in the virtual environment, but it did not reveal that participants would be exposed to a virtual height. Next, the experimenter measured participants' shoulder width (to calibrate the shoulder trackers) and their eye level (to position the fixation point for the postural stability test). Participants then completed the pre-immersion questionnaires via LimeSurvey (Sociodemographic and health questionnaire, STAI, MSSQ, SSQ, and ITQ), followed by the postural stability test. Afterward, the experimenter explained the practice trial, asked participants to remove their footwear and helped them put on the VR equipment. Prior to the immersion, the experimenter calibrated the virtual environment, which involved calibrating the location of the virtual plank and feet to match the physical counterparts and inputting participants' physical shoulder width to automatically set the narrow aperture width in the VR application.

Participants then completed the practice trial (Practice environment), lasting approximately 2 minutes. This immersion familiarized participants with the equipment (including the haptic feedback) and navigation in the virtual environment. Participants' task was to walk in a straight line on the wooden plank from the starting point (point A) to a post with a button and press the button (point B). Once participants pressed the button, they made a U-turn and walked back to the starting point (point A) and pressed a second button (see Berthiaume et al., submitted for an example trial). If participants collided with the virtual doors, the sensors on their shoulders vibrated.

After the practice trial, the experimenter responded to any questions posed by participants and explained the next immersion, either (1) Control condition or (2) Risk of falling condition (randomized order). Before this immersion, participants were asked to physically walk slowly for safety reasons (this instruction was given before each immersion, including the Practice environment). The immersion lasted approximately 2 minutes, and participants' task was identical to the Practice environment. However, in the Main environment, the elevator doors automatically closed to a narrower width when participants reached the midpoint between elevator A and elevator B. After this immersion, participants completed questionnaires (i.e., STAI, ITC-SOPI, and SSQ), followed by the postural stability test. The process was repeated for the immersion for the second experimental condition. Following the last immersion, a short debriefing session took place during which the experimenter explained the full objectives of the study and obtained participants' written consent for a second time. One participant refused to sign the form – thus, their data was removed and not used in any further analyses.

3. Results

The statistical analyses were carried out in SPSS, version 30 (IBM, 2025), with the final sample of 25 participants. First, descriptive analyses were performed to visualize the distribution of the data and to check for outliers. Inferential analyses were then conducted to test the study's hypotheses. Since the data were not normally distributed, the results from non-parametric analyses are reported.[2] Each analyzed variable was assessed for normality by visually inspecting the corresponding histogram (with an overlaid normal curve), examining the skewness and kurtosis values, and performing the Shapiro-Wilk's test. If at least two of the following criteria were met, the data were considered not normally distributed: (1) the data were visually skewed, (2) the skewness and kurtosis values were less than -1.5 or greater than 1.5, and/or (3) the p-value of the Shapiro-Wilk's test was less than .05 ($p < .05$). If a variable had several subscales (e.g., the SSQ), and the data on one or more of them were not normally distributed, all subscales were analyzed using non-parametric tests to avoid switching between statistical tests.

One participant had incomplete postural stability data (Risk of falling, eyes open only). Thus, some analyses with the postural stability data (COP parameters) included 24 participants rather than 25 participants. Since there were no technical issues with the VR component of the experimentation, the authors decided to include the participants' questionnaire and shoulder data to avoid losing valid data. For details on the steps followed to preprocess the shoulder data, see Appendix B.

Following the recommendation of Bouchard et al. (2021), raw SSQ scores (i.e., SSQ-Raw, with items related to anxiety) and corrected SSQ scores (SSQ-Anx, without the items related to anxiety) were calculated. The analyses in this section used raw SSQ scores to facilitate comparisons with other studies. However, additional results using corrected SSQ scores are reported in Appendix C (very similar results).

Corrections for multiple comparisons (Holm-Bonferroni) were applied within families to control the family-wise error rate. The families were defined by the study's main hypotheses. Specifically, Family 1 consisted of five variables with main hypotheses: ITC-SOPI Spatial and

[2] The results from the non-parametric tests are consistent with the results from the parametric alternatives (i.e., Pearson correlations and repeated-measures ANOVAs).

Naturalness subscales, shoulder rotations, STAI, and SSQ Total-Raw score. Family 2 comprised five variables from planned analyses without specific hypotheses: ITC-SOPI Engagement and Negative Effects subscales, SSQ Nausea-Raw and Oculomotor-Raw subscales, and collisions with doors. Finally, Family 3 included seven variables assessed in unplanned or exploratory analyses: COP parameters (95% confidence ellipse area and velocity[3]; eyes open and eyes closed), MSSQ total score, MSSQ child subscale score, and MSSQ adult subscale score. The following calculation was used for the Holm-Bonferroni correction: corrected alpha = .05/(k-m+1), where k = the number of variables in the family, m = the ranking of the variable's *p*-value in a given analysis. The raw *p*-values obtained from the statistical analyses were compared to the corrected alpha. The *p*-values only remained statistically significant if they were smaller than the corrected alpha.

The mean shoulder rotation angles, frequency of collisions with the doors, and questionnaire scores for the Control and Risk of falling conditions were rather similar (see Table 1, Table 2, and Table 3). Since the variables were compared across experimental conditions, the text and tables for these variables present the results by condition (i.e., Table 1, Table 2, Table 3, and Table 4, see additional details below).

Table 1 Descriptive statistics of shoulder rotation angles per experimental condition ($n = 25$)

Condition	*M*	*Mdn*	*SD*	Minimum	Maximum
Control	41.87	39.77	34.63	5.30	108.04
Risk of falling	38.57	14.08	36.61	3.59	99.80

The frequency of collisions with the doors was counted for each experimental condition in the two areas of interest (i.e., first shoulder approaching the doorway until this shoulder has

[3] Correlational analyses were also conducted using the total COP path length. However, the results were very similar to those obtained with the mean COP velocity. Thus, the results for the total path length are not reported.

entered the doorway; see Table 2). Collisions were defined in the following manner: No collisions = did not collide with the doors of either elevator (i.e., neither A nor B); One collision = collided with the doors of one elevator (i.e., A or B); Two collisions = collided with the doors of both elevators (i.e., A and B). Since there were two elevators, the maximum possible frequency of collisions for each participant is 2. The frequency of collisions was not statistically different between the conditions. Specifically, a Wilcoxon Signed-Rank test (non-parametric alternative to paired-samples t-test) was not statistically significant, regardless of whether the Holm-Bonferroni correction was applied: $Z = -1.00$, $p = .317$. For the Control condition, all (25 out of 25) participants collided with the doors of at least one elevator. For the Risk of falling condition, 24 out of 25 participants (96%) collided with the doors of at least one elevator. Additional results are presented in Appendix C.

Table 2 Frequency of participants who collided with the doors per experimental condition (n = 25)

Condition	No collisions	One collision	Two collisions
Control	0 (0%)	5 (20%)	20 (80%)
Risk of falling	1 (4 %)	5 (20%)	19 (76%)

Note. Results are presented as frequency followed by percentage in parentheses. No collisions = did not collide with the doors of either elevator (i.e., neither A nor B). One collision = collided with the doors of one elevator (i.e., A or B). Two collisions = collided with the doors of both elevators (i.e., A and B).

Table 3 Descriptive statistics of questionnaire scores and postural stability per experimental condition (SSQ includes items related to anxiety, i.e., items 1 and 9)

Variable	Control			Risk of falling		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*
STAI	27.40	26.00	6.17	29.00	29.00	7.24
ITC-SOPI–Spatial	3.89	3.78	.55	3.88	3.89	.47
ITC-SOPI–Engagement	3.67	3.62	.51	3.74	3.85	.50
ITC-SOPI–Naturalness	3.86	4.00	.81	3.82	4.00	.72
ITC-SOPI–Neg. Effects	1.55	1.50	.54	1.65	1.50	.66
SSQ–Nausea-Raw	.56	.00	.77	.48	.00	.82
SSQ–Oculomotor-Raw	1.48	.00	2.60	1.48	.00	2.49
SSQ–Total-Raw	2.04	.00	3.18	1.96	.00	2.99

EO–Ellipse	159.43	114.20	108.74	144.56	117.54	125.50
EO–Velocity	6.53	6.27	1.59	6.23	6.03	1.53
EC–Ellipse	171.94	101.46	144.74	220.56	146.51	237.48
EC–Velocity	7.79	7.62	2.07	7.94	7.61	2.38

Note. **Control** condition: n = 25 for questionnaires and n = 25 for postural stability data; **Risk of falling** condition: n = 25 for questionnaires and n = 24 for postural stability data with eyes open, n = 25 with eyes closed. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).

The results from Wilcoxon Signed-Rank tests indicated that anxiety (STAI), the mean shoulder rotations, self-reported presence (ITC-SOPI subscales), and postural stability (COP parameters) were also not significantly different across conditions, regardless of whether the Holm-Bonferroni correction was applied: $Z = -1.68$, $p = .093$ (STAI); $Z = -.63$, $p = .527$ (shoulder rotations); $Z = -.14$, $p = .891$ (ITC-SOPI Spatial); $Z = -1.14$, $p = .252$ (ITC-SOPI Engagement); $Z = -.79$, $p = .428$ (ITC-SOPI Naturalness); $Z = -1.18$, $p = .237$ (ITC-SOPI Negative Effects); $Z = -.57$, $p = .568$ (EO–Ellipse); $Z = -1.54$, $p = .123$ (EO–Velocity); $Z = -.55$, $p = .581$ (EC–Ellipse); $Z = -.31$, $p = .757$ (EC–Velocity). A Friedman test (non-parametric alternative to one-way repeated-measures ANOVA) was performed with the STAI score at pre ($M = 29.08$, $SD = 7.30$) to assess whether including this time point influenced the results. The results were not statistically significant, regardless of whether the Holm-Bonferroni correction was applied: $\chi^2_{(2)} = 2.88$, $p = .236$.

To test whether anxiety (STAI), presence (shoulder rotations and ITC-SOPI), and cybersickness (SSQ-Raw) within each experimental condition were correlated, Spearman correlations (non-parametric alternative to Pearson correlations) were conducted (see Table 4).[4] The results indicated no statistically significant correlation between the mean shoulder rotations

[4] The correlations reported in the paper were not adjusted for reliability (i.e., the observed/attenuated correlations are presented). However, the correlations adjusted for reliability (i.e., disattenuated correlations) were very similar. For additional details, please contact the corresponding author.

and the ITC-SOPI subscales within each condition (see Appendix C for scatterplots), regardless of whether the Holm-Bonferroni correction was applied. However, similar to the previous study (Berthiaume et al., submitted), the results showed a positive correlation between the STAI and the SSQ-Raw within both experimental conditions. In addition, several ITC-SOPI subscales were positively correlated. Most of the correlations remained significant after applying the Holm-Bonferroni correction. Additional Spearman correlations are reported in Appendix C.

To explore the relationship between anxiety (STAI) and postural stability (COP parameters) within each experimental condition, Spearman correlations were conducted (see Table 5). For descriptive statistics, see Table 2. Only the correlations between the COP parameters were statistically significant. Several correlations remained significant after applying the Holm-Bonferroni correction.

To explore whether cybersickness (SSQ-Raw) after the immersions was related to motion sickness (MSSQ) and postural stability (COP parameters) before the first immersion, descriptive statistics were performed (see Table 6), followed by Spearman correlations (see Table 7). Since the variables were compared across time (i.e., before versus after immersions), the text and tables report the results by immersion (time). There was a statistically significant correlation between the COP parameters with eyes closed and the SSQ Oculomotor-Raw subscale and the MSSQ Adult subscale. Moreover, there were statistically significant correlations within measures (e.g., the SSQ Nausea-Raw subscale was significantly correlated with the SSQ Oculomotor-Raw subscale). However, none of the correlations, except some within measures, remained significant after applying the Holm-Bonferroni correction.

Table 4 Spearman correlations between shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (n = 25)

Condition and Variable	1	2	3	4	5	6	7	8	9
Control									
1. Shoulder Rotation Angle	–								
2. STAI	-.30	–							
3. ITC-SOPI–Spatial	-.21	-.14	–						
4. ITC-SOPI–Engagement	-.15	-.02	**.59****	–					
5. ITC-SOPI–Naturalness	-.25	-.01	**.82****	**.62****	–				
6. ITC-SOPI–Neg. Effects	-.30	**.65****	.22	.08	.17	–			
7. SSQ–Nausea-Raw	-.27	**.56****	.09	-.02	.22	**.58****	–		
8. SSQ–Oculomotor-Raw	-.14	**.56****	.15	.04	.30	**.63****	**.79****	–	
9. SSQ–Total-Raw	-.21	**.62****	.10	.04	.24	**.65****	**.90****	**.97****	–
Risk of falling									
1. Shoulder Rotation Angle	–								
2. STAI	-.24	–							
3. ITC-SOPI–Spatial	-.23	-.01	–						
4. ITC-SOPI–Engagement	-.09	.08	**.71****	–					
5. ITC-SOPI–Naturalness	-.24	.14	**.86****	**.74****	–				
6. ITC-SOPI–Neg. Effects	-.16	**.51****	.30	.28	.31	–			
7. SSQ–Nausea-Raw	-.21	**.71****	.09	.11	.17	**.51****	–		
8. SSQ–Oculomotor-Raw	-.05	**.53***	-.25	-.21	-.13	.31	**.70****	–	
9. SSQ–Total-Raw	-.11	**.61****	-.16	-.14	-.05	.38	**.80****	**.98****	–

Note. SSQ-Raw includes items related to anxiety (i.e., items 1 and 9).
*p < .05. **p < .01.

Table 5 Spearman correlations between anxiety and postural stability by experimental condition

Condition and Variable	1	2	3	4	5
Control					
1. STAI	–				
2. EO–Ellipse	-.17	–			
3. EO–Velocity	.05	**.51****	–		
4. EC–Ellipse	-.04	**.55****	**.43***	–	
5. EC–Velocity	.04	**.69****	**.68****	**.74****	–
Risk of falling					
1. STAI	–				
2. EO–Ellipse	-.25	–			
3. EO–Velocity	-.31	.34	–		
4. EC–Ellipse	-.33	**.55****	**.43***	–	
5. EC–Velocity	-.25	.24	**.66****	**.69****	–

Note. **Control** condition: $n = 25$ for questionnaires and $n = 25$ for postural stability data; **Risk of falling** condition: $n = 25$ for questionnaires and $n = 24$ for postural stability data with eyes open, $n = 25$ with eyes closed. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
*$p < .05$. **$p < .01$.

Table 6 Descriptive statistics of questionnaire scores and postural stability per immersion (time)

Variable	Pre			Immersion 1			Immersion 2		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*	*M*	*Mdn*	*SD*
SSQ–Nausea-Raw	2.04	1.00	4.16	.48	.00	.87	.56	.00	.71
SSQ–Oculomotor-Raw	2.64	2.00	3.30	1.40	.00	2.48	1.56	.00	2.60
SSQ–Total-Raw	4.68	2.00	7.31	1.88	.00	3.14	2.12	1.00	3.03
EO–Ellipse	102.22	87.25	59.53	163.90	111.32	145.79	132.73	101.78	78.29
EO–Velocity	6.08	5.70	1.66	6.49	6.27	1.70	6.29	6.11	1.42
EC–Ellipse	139.12	93.83	110.37	196.55	108.10	215.46	159.79	128.64	104.63
EC–Velocity	8.20	8.39	1.82	7.99	7.90	2.37	7.75	7.45	2.09
MSSQ–Child	4.96	3.86	4.77	–	–	–	–	–	–
MSSQ–Adult	3.80	2.00	4.58	–	–	–	–	–	–
MSSQ–Total	8.76	5.14	9.07	–	–	–	–	–	–

Note. **Pre** = Before the first immersion ($n = 25$ for questionnaires and $n = 25$ for postural stability data); **Immersion 1** = After the first immersion ($n = 25$ for questionnaires and $n = 24$ for postural stability data with eyes open, $n = 25$ with eyes closed); **Immersion 2** = After the last (second) immersion ($n = 25$ for questionnaires and $n = 25$ for postural stability data). SSQ-Raw includes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).

Table 7 Spearman correlations between cybersickness, postural stability, and motion sickness by immersion (time)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. SSQ–Nausea-Raw (Imm. 1)	–												
2. SSQ–Oculomotor-Raw (Imm. 1)	**.72****	–											
3. SSQ–Total-Raw (Imm. 1)	**.81****	**.99****	–										
4. SSQ–Nausea-Raw (Imm. 2)	**.68****	**.66****	**.71****	–									
5. SSQ–Oculomotor-Raw (Imm. 2)	**.51****	**.62****	**.65****	**.76****	–								
6. SSQ–Total-Raw (Imm. 2)	**.61****	**.71****	**.74****	**.87****	**.97****	–							
7. EO–Ellipse (Pre)	.16	.34	.31	.07	.14	.14	–						
8. EO–Velocity (Pre)	.08	-.19	-.13	.20	-.02	.00	-.19	–					
9. EC–Ellipse (Pre)	.26	.25	.26	-.06	-.03	.00	**.56****	-.15	–				
10. EC–Velocity (Pre)	-.34	**-.40***	**-.41***	-.02	-.08	-.12	-.33	**.72****	-.25	–			
11. MSSQ–Child (Pre)	.26	.05	.11	.25	.23	.23	-.02	-.07	-.20	-.25	–		
12. MSSQ–Adult (Pre)	.25	.16	.18	.10	.11	.09	.31	-.15	.02	-.35	**.77****	–	
13. MSSQ–Total (Pre)	.23	.08	.12	.19	.17	.16	.08	-.17	-.16	-.32	**.96****	**.88****	–

Note. **Pre** = Before the first immersion (n = 25 for questionnaires and n = 25 for postural stability data); **Immersion 1** = After the first immersion (n = 25 for questionnaires); **Immersion 2** = After the last (second) immersion (n = 25 for questionnaires). SSQ-Raw includes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
*p < .05. **p < .01.

Following the correlational analysis, Friedman tests were performed to assess whether cybersickness and postural stability were significantly different over time. The results indicated statistically significant differences in SSQ-Raw scores over time: $\chi^2_{(2)} = 4.41$, $p = .110$ (Nausea subscale); $\chi^2_{(2)} = 6.14$, $p = .047$ (Oculomotor subscale); $\chi^2_{(2)} = 4.88$, $p = .087$ (Total score). However, only the results for the Oculomotor subscale score remained significant after applying the Holm-Bonferroni correction. Furthermore, the ellipse area with eyes open was the only COP parameter that significantly differed over time: $\chi^2_{(2)} = 14.58$, $p < .001$ (95% confidence ellipse area, eyes open). This result remained significant after applying the Holm-Bonferroni correction. The remaining COP parameters did not significantly differ over time, regardless of whether the Holm-Bonferroni correction was applied: $\chi^2_{(2)} = 3.58$, $p = .167$ (velocity, eyes open); $\chi^2_{(2)} = .56$, $p = .756$ (95% confidence ellipse area, eyes closed); $\chi^2_{(2)} = 1.04$, $p = .595$ (velocity, eyes closed). Additional results are reported in Appendix C.

4. Discussion

The study put forward the following hypotheses: (1) shoulder rotation angles will be significantly positively correlated with self-reported presence, (2) self-reported presence and anxiety will be significantly higher in the Risk of falling condition than the Control condition, and (3) self-reported presence, anxiety, and cybersickness within each experimental condition will be significantly positively correlated. Additional exploratory analyses investigated the relationship between self-reported cybersickness after the immersions and postural stability and self-reported motion sickness before the first immersion. Exploratory analyses also examined the relationship between anxiety and postural stability within each experimental condition. The results did not support Hypothesis 1 or 2. However, they partially supported Hypothesis 3. Overall, the results from the analyses were similar to Berthiaume et al. (submitted), suggesting that the lack of significant findings may be more than just a coincidence. Specifically, similar to Berthiaume et al. (submitted), the current study did not find a statistically significant correlation between self-report and behavioral measures of presence. Furthermore, similar to the previous study, the mean STAI scores were relatively low, even with the improvements made to the virtual environment to increase the perception of height. The results also indicated that there was no statistically significant correlation between self-reported presence and anxiety. The findings are discussed in more detail below.

As expected, participants rotated their shoulders to cross the narrow doorways and displayed individual variability in rotation amplitude. However, the correlations between shoulder rotation angles (behavioral indicator of presence) and self-reported presence were small and not significant, which do not support Hypothesis 1. These results align with Berthiaume et al. (submitted), who also did not find statistically significant correlations between these variables. The replication of the findings suggests that behavioral and self-report measures in VR might not necessarily align. A systematic review reported a similar effect between physiological and self-report measures of anxiety in VR-based exposure treatments (Ernst et al., 2024). Similarly, Maymon et al. (2024) found a non-significant relationship between self-reported presence and physiological measures (heart rate and skin conductance) when participants were exposed to a virtual environment simulating heights. In contrast, the relationship between self-reported presence and anxiety was significant. While Maymon et al. (2024) did not find a statistically significant correlation between self-reported presence and physiological measures, other studies have reported a significant correlation between self-reported presence and heart rate (e.g., Higuera-Trujillo et al., 2017; Meehan et al., 2002; Wiederhold et al., 2001).

The results from these studies may be explained by the phenomena in psychology known as discordance between self-report and behavioral measures. Specifically, prior research indicated that self-reported fear and behavior (e.g., avoidance, performance) do not necessarily converge (e.g., Benoit Allen et al., 2015; Craske & Craig, 1984; Hodgson & Rachman, 1974; Rachman & Hodgson, 1974). For instance, individuals may report high fear but do not avoid a feared object or situation, or conversely report low fear and display avoidance (Hodgson & Rachman, 1974; Rachman & Hodgson, 1974). In other words, the correlation between self-report and behavioral measures may not be statistically significant (discordance). It is possible that self-report and behavioral measures of presence in VR also show a pattern of discordance. Therefore, using a variety of measures can provide a more comprehensive understanding of user experience in VR, particularly when the aim is to reproduce behavior from the physical environment. It could be useful in future work to employ different behavioral measures to evaluate other behaviors in anxiety-inducing environments, such as walking patterns.

Furthermore, similar to Berthiaume et al. (submitted), the current study observed some participants compressing their shoulders (as well as rotating them) to pass through the narrow virtual doors. Body compression is typically not measured in virtual environments (Bhargava et al., 2021; Bhargava et al., 2023). Future studies investigating narrow aperture passability in VR should consider using methods to assess and record body compression.

The mean shoulder rotation angles in the current study were consistent with the previous study (Berthiaume et al., submitted) (Control: Study 1 = 44.64° versus Study 2 = 41.87°; Risk of falling: Study 1 = 46.22° versus Study 2 = 38.57°). However, the frequency of collisions with the elevator doors differed across both studies. Specifically, in Berthiaume et al. (submitted), the frequency of collisions was significantly higher in the two conditions with the risk of falling than the control condition. However, in the current study, the frequency of collisions was similar in both conditions, and most participants collided with the elevator doors. This suggests that participants may have either misperceived or miscalculated the aperture passability or were distracted by elements in the virtual environment (e.g., the warning sign on the elevator doors), which contributed to collisions with the doors. The discrepancy in the frequency of collisions between the studies may be due to methodological differences (e.g., haptic feedback, the warning sign). Finally, similar to the previous study, some participants touched the virtual doors with their hands, even though a warning sign on each door instructed them to keep their hands clear of the doors. The sign was intended to deter participants from touching the doors and encourage them to rotate their shoulders when passing through the narrow doors, but these results suggest that it was ineffective. Such warning signs (with similar wording) are common on construction sites, but participants may have been unsure how to interpret the sign due to unfamiliarity with this context or the wording.

The studies conducted by Lepecq et al. (2009) and Mestre et al. (2016) inspired the methodology for the study by Berthiaume et al. (submitted) and the current study. Lepecq et al. and Mestre et al. did not use a self-report measure of presence. However, their results related to participants' shoulder rotations could help explain the ones from the current study. Specifically, their results showed a significant increase in shoulder rotation for a ratio between aperture width and shoulder width (A/S) of approximately 1.2 to 1.4. Although both studies obtained a similar critical aperture to shoulder ratio, the occurrence of collisions varied between the studies. In their study, Lepecq et al. (2009) used a CAVE setup (i.e., participants' physical body was visible) and exposed all participants to the same experimental condition: a virtual environment with sliding doors and auditory stimuli (spatialized sound of doors closing). The authors found that only two out of nineteen participants collided with the doors. In their study, Mestre et al. (2016) used a VR headset (i.e., participants' physical body was not visible) and exposed participants to four experimental conditions: (1) Visual only (full-body avatar), (2) Haptic feedback only (vibrations), (3) No visual + no haptic feedback, and (4) Visual + haptic feedback. The virtual environment and experimental task were similar to Lepecq et al. (2009). The results revealed that participants collided with the doors in almost 50% of the trials in the conditions without a full-body avatar. Overall, there seemed to be a lower occurrence of collisions for small apertures in the Visual + haptic feedback condition, followed by the Visual only and Haptic feedback only conditions, and finally the No visual + no haptic condition. This suggests that integrating both a visual body representation and haptic feedback could help with collision avoidance.

The shoulder rotation angles in Berthiaume et al. (submitted) and the current study are smaller than those reported by Lepecq et al. (2009) and Mestre et al. (2016). Moreover, the frequency of collisions is higher in Berthiaume et al. (submitted) and the current study. Variations in equipment (e.g., pack frame with shoulder trackers in the current study versus motion capture in previous studies) may have contributed to the differences observed between the studies. The differences could also stem from incorporating a visual representation of participants' physical shoulders in the virtual environment (full-body avatar, Mestre et al., 2016). It is possible that haptic feedback alone might have a more limited impact on behavior unless a visual body representation is also added. This effect may be delayed, after unsuccessful trials (i.e., trials with collisions). During the debriefing session of the current study, one participant reported being aware that they would be unable to "fit through" the narrow virtual doorways if they walked facing forward. However, since they could not view their physical shoulders (i.e., no visual cues), they were uncertain whether to compress or rotate their shoulders, and to what extent, to cross the doorways, as it was challenging to determine their shoulders' exact spatial position. It could be useful to incorporate a visual representation of participants' physical shoulders in future work, as embodiment can influence user behavior (e.g., Mestre et al., 2016).

Similarly, during the immersions of the current study, a few participants reported being uncertain about how to proceed when they arrived at the narrow doorways. It would be useful to conduct an identical experiment in the physical environment and compare behaviors, given that affordances may be more apparent in the physical context. For instance, it is likely clear in the physical environment that one must rotate or compress their shoulders to fit through narrow spaces, but it may be less apparent in VR, particularly when users lack a visual body representation and the consequences of their actions are unclear. It may also be beneficial to examine whether immersion in a virtual environment that includes a corresponding physical structure (e.g., wooden pillars) enhances presence and elicits more realistic behavior.

Self-reported presence and anxiety were not significantly higher in the Risk of falling condition, which does not support Hypothesis 2. Indeed, the results showed that presence (subscale scores on the ITC-SOPI) and anxiety (total score on the STAI) did not significantly differ across experimental conditions. The subscale scores on the ITC-SOPI and the total scores on the STAI are aligned with Berthiaume et al. (submitted). In both studies, the subscale scores on the ITC-SOPI are similar to previous studies (e.g., Freeman et al., 2005; Lessiter et al., 2001). It could be useful in future studies to administer a different self-report measure of presence, such as the Igroup Presence Questionnaire (Schubert et al., 2001) or the Slater-Usoh-Steed Presence Questionnaire (Usoh et al., 2000). In addition, the total scores on the STAI are unexpectedly low, with mean scores in each experimental condition below 30. These scores are inconsistent with previous studies (e.g., Felnhofer et al., 2014), although one study (Gromer et al., 2018) reported mean STAI scores of 33.29 for the "low height anxious" group. Total scores on the STAI can range from a minimum score of 20 to a maximum score of 80 (Spielberger et al., 1983).

The low scores may be due to the wording of the instructions in the STAI, which assessed anxiety in the present moment ("[…] indicate how you feel *right* now, that is, *at this moment*") rather than during the immersion ("[…] indicate how you felt *during the immersion*"). Participants completed the questionnaires post-immersion, outside of VR, which may have affected presence and anxiety, as they were measured retrospectively. This method was chosen because the questionnaires were relatively long. In addition, it allowed to compare the study's results with other studies that administered questionnaires post-immersion, outside of VR (e.g., Bouchard et al., 2008; Gromer et al., 2019; Kisker et al., 2021). However, future studies should consider integrating a brief assessment directly into the virtual environment, which would allow to assess presence and anxiety in real-time during the immersion. Anecdotally, during the Risk of falling condition, some participants verbally reported perceiving the height (e.g., feeling high above the ground). The evaluation of anxiety in real-time would allow to better capture these responses. Some participants may have also looked ahead (rather than down) during the immersion, which could have led to lower anxiety scores. Moreover, Berthiaume et al. (submitted) and the current study used convenience sampling, and no participants had a phobia of heights. Previous studies suggest that presence is higher when the virtual environment contains a feared object or situation (e.g., Kisker et al., 2021). Future studies could recruit a sample of participants with a phobia of heights.

Hypothesis 3 was partially supported. Specifically, the correlation between self-reported presence (ITC-SOPI subscales) and anxiety (STAI) and between presence and cybersickness (SSQ-Raw) was not significant. However, similar to Berthiaume et al. (submitted), the correlation between anxiety and cybersickness was significant. Previous studies examining the relationship between presence and anxiety and presence and cybersickness have indicated mixed results. For instance, some studies found a significant correlation between these variables (e.g., Bouchard et al., 2008; Liu & Uang, 2011), but others revealed negative or non-significant correlations (e.g., Ling et al., 2012; Weech et al., 2020). It is possible that the relatively low mean total scores on the STAI contributed to the non-significant correlation between presence and anxiety. In other words, the low scores on the STAI may have resulted in low dispersion in the data and smaller correlations between the variables. The significant correlation between anxiety and cybersickness aligns with previous studies (e.g., Bouchard et al., 2007; Bouchard et al., 2021), with an overlap between some symptoms of anxiety and cybersickness (e.g., general discomfort, difficulty concentrating). For this reason, research on VR may benefit from using alternative scoring methods to distinguish between anxiety and cybersickness.

The results indicated that cybersickness (SSQ-Raw) after the immersions did not significantly correlate with postural stability (COP parameters) or motion sickness (MSSQ) before the first immersion. Previous studies obtained mixed results from correlations between cybersickness and postural stability (e.g., Arcioni et al., 2019; Litleskare, 2021), with some literature suggesting that postural instability can predict the likelihood of cybersickness (e.g., Arcioni et al., 2019; Risi & Palmisano, 2019). These studies experimentally manipulated cybersickness (e.g., participants continuously rotated their heads or watched a video with pronounced motion). In contrast, the current study did not experimentally manipulate or induce cybersickness in participants, and cybersickness scores were relatively low after both immersions (i.e., mean Total SSQ-Raw scores below 5). However, one immersion was conducted in a high environment, which could evoke instability (Coelho & Balaban, 2015). Similar to the scores on the STAI, it is possible that the low cybersickness scores resulted in low dispersion in the data and smaller correlations between the variables. Considering the mixed results from previous studies and the results from the current study, further research is needed to better understand the relationship between cybersickness and postural stability. Being able to predict cybersickness before users are immersed in VR would allow to better customize their experience during the immersion. However, future work is required to evaluate whether postural stability is an adequate measure and predictor of cybersickness.

Moreover, the correlation between anxiety (STAI) and postural stability (COP parameters) was not statistically significant across conditions. This result is inconsistent with a previous study (Wuehr et al., 2019), which found a positive correlation between subjective fear ratings and sway velocity. However, Wuehr et al. (2019) asked participants to rate their fear on a scale of 0 to 10 and not the STAI. The COP parameter values in the current study were similar to Chander et al. (2021) and Simeonov et al. (2005), who examined the relationship between anxiety and postural stability in the context of virtual heights. Specifically, Chander et al. (2021) showed a mean COP 95% ellipsoid sway area of 3.20 cm^2 (320 mm^2) and an average sway velocity of 5.10 cm/s (51 mm/s) in the "No VR" condition (the most similar condition to the "pre" timepoint in the current study). The results also indicated that the COP sway area was larger at heights than at the ground level in VR. Similarly, Simeonov et al. (2005) found a mean sway velocity of approximately 2 cm/s (20 mm/s) in the "Real, Firm Ground" condition. Overall, the mean sway velocity was larger at heights than at the ground level in VR. The current study did not assess postural stability while participants were exposed to the virtual height. However, it would be useful for future research to do so and further investigate the relationship between anxiety, cybersickness, and postural stability.

Limitations and future directions

One potential limitation of the study is that the virtual environment did not include a visual representation of participants' physical shoulders, which may have been confusing to participants (e.g., unclear whether they could pass through the doors without rotating their shoulders). An attempt was made to implement a visual representation, but during testing, it was not possible to see the virtual objects representing the shoulders without physically turning one's head in an uncomfortable position due to the VR equipment. Future research would benefit from implementing a visual body representation.

A second potential limitation is that participants were not explicitly asked why they performed certain behaviors (e.g., making a smaller rotation and compressing their shoulders rather than making a larger rotation). For example, previous studies included passability judgments, where they explicitly asked participants if they judged various doorways as passable without needing to physically rotate their body (e.g., Bhargava, Lucaites, et al., 2020; Bhargava, Solini, et al., 2020; Geuss et al., 2010). However, in these studies, participants typically did not actually walk through the doorways following the passability judgments. Future work could implement a task involving both passability judgments and physically crossing the doorways.

Finally, a third limitation is that postural stability was only assessed before and after the immersions rather than continuously while walking during the immersions (e.g., Wang et al., 2025). Thus, it is unclear whether participants' postural stability was directly affected while they were immersed in the virtual environments. The current study's design did not allow the continuous measurement of postural stability, since it used force plates and participants' task involved physical walking. However, results still challenge the notion that prior postural instability could lead to cybersickness (e.g., Arcioni et al., 2019; Risi, D., & Palmisano, 2019). It remains unclear whether postural stability can be used to predict and/or objectively measure cybersickness (Litleskare, 2021). Future studies should consider using an alternative measure of postural stability or a different task.

5. Conclusion

The current study's main aim was to evaluate a behavioral measure of presence in VR. The study also explored the relationship between presence, anxiety, cybersickness, and postural stability. The results indicated no statistically significant correlation between the self-report and the behavioral measures of presence, replicating previous findings. Taken together, these results suggest that subjective and behavioral measures of presence may show a pattern of discordance, a phenomenon known in the field of emotion. It is possible that self-report and behavioral measures do not necessarily need to converge for virtual environments to be effective. Future studies should consider using a variety of self-report and behavioral measures to assess presence, particularly when the goal is to evaluate the correspondence of user behavior in VR and the physical environment. Moreover, future work could benefit from incorporating a visual body representation in VR and comparing behavior in both VR and the physical environment.

While there was no correlation between the self-report and behavioral measures of presence, the correlation between anxiety and cybersickness was statistically significant. Given their overlapping symptoms (e.g., general discomfort, difficulty concentrating), distinguishing between the two conditions can be challenging. This could have potential implications for the evaluation of anxiety-inducing virtual environments. Future studies should consider using methods to distinguish between anxiety and cybersickness (e.g., alternative scoring methods), particularly in the context of psychotherapy and anxiety-related applications. Future research is needed to further examine the relationship between anxiety, cybersickness, and postural stability.

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Appendix A

Verbal instructions to participants for postural stability test

Trial with eyes open (first trial):

"*We will now do a test to measure postural stability, or balance. We will do two trials: one trial with eyes open and a second trial with eyes closed. Each trial will last 25 seconds with a 20-second break between the trials.*

We will start with the trial with eyes open. Before beginning the trial, I will give you some instructions and do a demonstration. During the trial, you will stand with one foot on each platform, ensuring your feet are hip-width apart and parallel. Your weight should be evenly distributed between both feet. Stand up straight with your shoulders relaxed and your arms hanging naturally at your sides without your hands touching your legs. Try to remain as still as possible. Breathe naturally.

I will let you know when the trial is finished. If you feel uncomfortable or need to stop, please let me know and we will stop the trial. Do you have any questions before we start?

When you are ready, you can stand on the platforms. I will ask that you look at the fixation point during the trial. We will begin the trial now."

After the trial with eyes open:

"*We will take a short 20-second break and then we will move on to the second trial. You can remain on the plates.*"

Trial with eyes closed (second trial):

"*We will now move on to the trial with eyes closed. I will ask that you look at the fixation point. Once you feel steady, close your eyes, and keep them closed for the duration of the trial. We will begin the trial now.*"

Below are the instructions in French for francophone participants.

Essai yeux ouverts (premier essai) :

« Nous allons maintenant réaliser un test pour mesurer la stabilité posturale, ou l'équilibre. Nous ferons deux essais : *un essai avec les yeux ouverts et un second essai avec les yeux fermés. Chaque essai durera 25 secondes avec une pause de 20 secondes entre les essais.*

Nous allons commencer par l'essai avec les yeux ouverts. Avant de débuter l'essai, je vais vous donner quelques consignes et faire une démonstration. Pendant le test, vous vous tiendrai avec un pied sur chaque plateforme, en veillant à ce que vos pieds soient écartés à la largeur des hanches et parallèles. Votre poids doit être réparti uniformément entre les deux pieds. Tenez-vous droit(e), avec les épaules détendues et les bras relâchés le long du corps sans que vos mains touchent vos jambes. Essayez de rester aussi immobile que possible. Respirez naturellement.

Je vous dirai quand l'essai est terminé. Si vous vous sentez mal à l'aise ou si vous avez besoin d'arrêter, veuillez me le faire savoir et nous arrêterons l'essai. Avez-vous des questions avant que nous commencions ?

Quand vous êtes prêt(e), vous pouvez monter sur les plateformes. Je vous demanderais de regarder le point de fixation pendant l'essai. Nous allons commencer l'essai maintenant. »

Après l'essai avec les yeux ouverts :

« Nous allons prendre une courte pause de 20 secondes et nous passerons ensuite au deuxième essai. Vous pouvez rester sur les plateformes. »

Essai yeux fermés (deuxième essai) :

« Nous allons maintenant passer à l'essai avec les yeux fermés. Je vous demanderais de regarder le point de fixation jusqu'à ce que vous vous sentiez stable, ensuite fermez les yeux pendant toute la durée de l'essai. Nous allons commencer l'essai maintenant. »

Appendix B

VR shoulder data preprocessing and analysis

The steps followed to preprocess and analyze the shoulder rotation data for the current study were similar to Berthiaume et al. (submitted). This appendix describes the main differences between the two studies. The sections below provide additional details. The Python scripts referred to in the next sections contain additional notes about the procedure followed.

Python variable names

This section lists the main variable names used in the Python scripts:

- ParticipantID: An individual participant's ID number.
- EVCondition: The current experimental condition (i.e., Control or Risk of falling).
- WalkingDirection: The direction of walking, where 0 = Door A to Door B ("Going"); 1 = Door B to Door A ("Returning").
- DoorName: The name of the doorway/elevator being entered or exited (i.e., Door A or Door B).

Step 1: Plot data

Step 1 was identical in both studies (see Berthiaume et al., submitted for additional details). Specifically, two Python scripts generated interactive 3D plots ("01_plot_shoulder_data_3D.py") and 2D plots ("02_plot_shoulder_data_2D.py") with original/unprocessed data. The data were visually inspected in the plots and in a Unity application (developed by a technician at the laboratory) to identify any anomalous data points. No participants had any anomalous data points in the current study.

Step 2: Preprocess data

Following the visualization of the data, the data were preprocessed for further analysis using the Python script “03_shoulder_data_preprocess.py” (e.g., correcting WalkingDirection set incorrectly during the experimentation). The preprocessed data were used in the following steps.

Step 3: Identify areas of interest

The areas of interest for each unique combination of participant (ParticipantID), condition (EVConditon), walking direction (WalkingDirection), and doorway (DoorName) were identified using the Python script “04_shoulder_data_doorways_in_doorway.py”. The identified areas of interest were used to filter the shoulder data in the next step. The Python script followed the steps below (see the script for additional details):

1. Compute the start and the end of the doorway for Door A and Door B.
    a. Start of doorway = center of doorway[1] + 0.05 m (depth of doorway = 0.10 m)
    b. End of doorway = center of doorway - 0.05 m (depth of doorway = 0.10 m)
2. Subtract 1.5 seconds from the start of the doorway (see Berthiaume et al., submitted for a more detailed explanation).
3. Generate plots highlighting the areas of interest.

Step 4: Extract and analyze data

Step 4 was identical in both studies (see Berthiaume et al., submitted for additional details). Specifically, the frequency of shoulder collisions with the doors was counted (“05_shoulder_data_collisions.py”) and the mean shoulder rotation angles in the areas of interest were calculated (“06_shoulder_data_rotations.py”). The frequency of shoulder collisions and the mean shoulder rotation angles for each area of interest were then manually entered in SPSS, which was used for further descriptive and inferential statistical analyses.

[1] Unity automatically recorded the position of the center of the doorways during the experimentation.

Appendix C

Additional results, figures, and tables

This appendix contains additional results, figures, and tables that did not directly address the study's hypotheses. For analyses comparing data across experimental conditions, the text and tables present the results by condition. For analyses comparing data over time, they report the results by immersion (time). It is important to note that the results from all analyses in this appendix are exploratory due to unbalanced groups and the relatively small sample size per group. Furthermore, most of the measures analyzed do not follow a normal distribution.

Many analyses in this appendix were performed using the SSQ. Two methods were used to score the SSQ for correlational analyses specifically examining the relationship between the SSQ and the STAI. Bouchard et al. (2021) recommended these methods after finding a correlation between certain SSQ items and anxiety (STAI). Specifically, one scoring method used raw SSQ scores (i.e., SSQ-Raw, with items related to anxiety) and the second used corrected SSQ scores (i.e., SSQ-Anx, without these items). Two SSQ items are related to anxiety: item 1 (Nausea subscale) and item 9 (Oculomotor subscale). The corrected Nausea score (SSQ-Nausea-Anx) excludes item 1, the corrected Oculomotor score (SSQ-Oculomotor-Anx) excludes item 9, and the corrected Total score (SSQ-Total-Anx) excludes both items 1 and 9. Each relevant table below indicates whether the raw or the corrected scores are reported.

Individual characteristics

The sample consisted of 15 women and 10 men. Table 8 and Figure 6 presents descriptive statistics of individual characteristics (e.g., age, prior VR experience). Table 9 reports correlations between individual characteristics and the main variables of interest (i.e., shoulder rotations, presence, anxiety, cybersickness, and postural stability). Some correlations were statistically significant, but few remained significant after applying the Holm-Bonferroni correction. Raw SSQ scores (SSQ-Raw) were used to facilitate comparisons between studies.

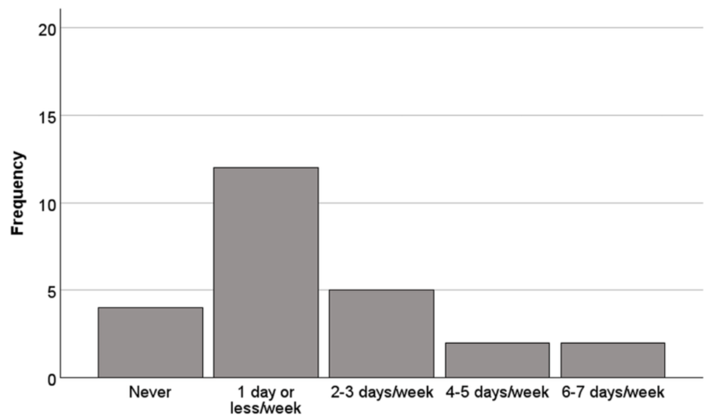
Table 8 Descriptive statistics of individual characteristics (*n* = 25)

Variable	*M*	*Mdn*	*SD*	Minimum	Maximum
Shoulder width	41.00	41.00	3.38	35.00	50.00
Age	21.96	21.00	3.74	18.00	32.00
ITQ–Total	71.04	74.00	16.98	46.00	101.00
BSQ	19.32	17.00	10.11	8.00	40.00
STAI (Pre)	29.08	29.00	7.30	20.00	40.00
AQ–Anx	31.92	29.00	18.00	2.00	72.00

Note. **ITQ** = Immersive Tendencies Questionnaire. **BSQ** = Body Shape Questionnaire. **AQ–Anx** = Acrophobia Questionnaire, Anxiety subscale. Participants completed the questions related to individual characteristics and the ITQ at pre only. Participants completed the AQ and the BSQ at post only.

Figure 6 Distribution of prior experience with video gaming and with VR (*n* = 25)

(A) Experience with video gaming on PC or console (days)



(B) Experience with VR (days)

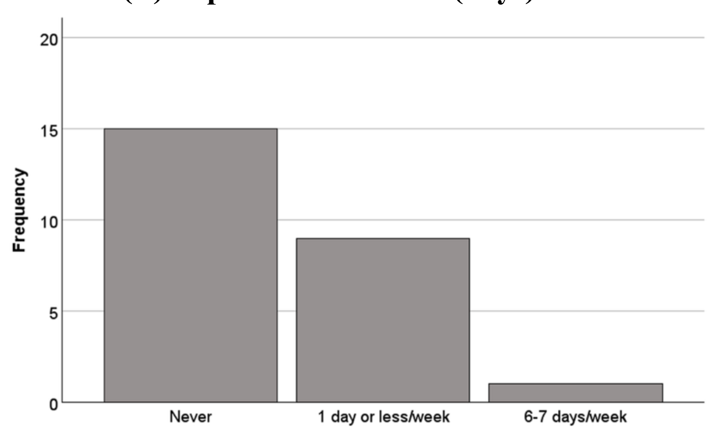


Table 9 Correlations between individual characteristics, shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (SSQ includes items related to anxiety, i.e., items 1 and 9)

Condition and Variable	Shoulder width	Age	ITQ–Total	BSQ	STAI (Pre)	AQ–Anx	Video gaming exp.	VR exp.	Gender
Control									
1. Shoulder Rotation Angle	.06	.27	.04	-.04	-.17	.00	-.08	.03	-.13
2. STAI	.29	.03	.06	.19	**.71****	-.19	-.03	-.06	-.08
3. ITC-SOPI–Spatial	**-.40***	-.23	.07	-.06	.13	.18	-.17	-.02	**.49***
4. ITC-SOPI–Engagement	-.28	-.23	.33	.07	.10	.02	.04	-.11	.39
5. ITC-SOPI–Naturalness	**-.40***	-.07	.16	-.08	.01	.02	-.09	-.01	**.44***
6. ITC-SOPI–Neg. Effects	.18	-.16	-.14	.11	**.75****	.18	.01	-.16	-.08
7. SSQ–Nausea-Raw	-.19	-.07	-.10	.04	**.44***	.15	-.20	.23	.17
8. SSQ–Oculomotor-Raw	.02	.07	-.06	-.09	**.51****	.09	-.19	.00	.19
9. SSQ–Total-Raw	-.07	-.02	-.09	-.03	**.56****	.08	-.20	.05	.19
10. EO–Ellipse (Pre)	.04	-.14	-.02	.27	.30	.34	-.09	.24	.33
11. EO–Velocity (Pre)	.06	-.14	-.06	.07	.18	.03	.33	.01	-.07
12. EC–Ellipse (Pre)	.01	.32	.14	-.02	-.22	-.04	-.04	.15	.18
13. EC–Velocity (Pre)	.36	.03	-.06	.15	.03	-.01	.20	-.21	-.08
14. EO–Ellipse	.25	.07	.05	.15	-.13	.06	.15	.05	-.05
15. EO–Velocity	.11	-.12	-.24	.11	.12	-.22	.16	.14	.10
16. EC–Ellipse	.16	.01	.06	.11	.26	.21	.15	.04	-.08
17. EC–Velocity	.31	-.03	-.02	.23	.10	.09	.22	-.10	-.03
18. MSSQ–Child (Pre)	-.14	-.10	.28	.00	.11	.35	.02	.20	.24
19. MSSQ–Adult (Pre)	-.11	-.06	.21	-.18	-.08	.11	.02	.16	-.01
20. MSSQ–Total (Pre)	-.16	-.09	.27	-.05	.00	.27	.02	.19	.12
Risk of falling									
1. Shoulder Rotation Angle	.10	.36	.05	.05	-.10	-.08	-.11	.02	-.13
2. STAI	.29	-.01	.10	.13	**.64****	.03	.00	.01	-.13
3. ITC-SOPI–Spatial	-.26	-.27	.14	.02	.01	.28	-.02	.01	**.40***
4. ITC-SOPI–Engagement	-.11	-.11	.34	.07	.06	-.07	.24	-.31	.12
5. ITC-SOPI–Naturalness	-.24	-.09	.21	.06	-.07	.06	.00	-.04	.23

6. ITC-SOPI–Neg. Effects	.15	.07	-.03	-.11	**.64****	-.02	.11	-.06	-.06
7. SSQ–Nausea-Raw	-.08	-.17	-.01	.21	**.52****	-.05	-.06	.10	.08
8. SSQ–Oculomotor-Raw	-.14	.13	-.20	-.08	.39	-.30	-.27	.19	.13
9. SSQ–Total-Raw	-.14	.06	-.17	-.01	**.46***	-.25	-.24	.18	.13
10. EO–Ellipse (Pre)	–	–	–	–	–	–	–	–	–
11. EO–Velocity (Pre)	–	–	–	–	–	–	–	–	–
12. EC–Ellipse (Pre)	–	–	–	–	–	–	–	–	–
13. EC–Velocity (Pre)	–	–	–	–	–	–	–	–	–
14. EO–Ellipse	-.02	.02	-.08	**.41***	.02	-.09	.05	.05	-.16
15. EO–Velocity	.26	.11	-.13	.05	-.03	-.14	**.47***	.04	-.17
16. EC–Ellipse	-.05	-.15	.18	.25	.06	.29	-.05	-.06	.30
17. EC–Velocity	.24	-.04	-.01	.17	.13	.26	.19	-.06	.01
18. MSSQ–Child (Pre)	–	–	–	–	–	–	–	–	–
19. MSSQ–Adult (Pre)	–	–	–	–	–	–	–	–	–
20. MSSQ–Total (Pre)	–	–	–	–	–	–	–	–	–

Note. Spearman correlations were performed for all individual characteristics, except gender and prior experience with video gaming and with VR where point-biserial correlations were conducted. **Control** condition: *n* = 25 for questionnaires and *n* = 25 for postural stability data; **Risk of falling** condition: *n* = 25 for questionnaires and *n* = 24 for postural stability data with eyes open, *n* = 25 with eyes closed. **Pre** = Before the first immersion. **ITQ** = Immersive Tendencies Questionnaire. **BSQ** = Body Shape Questionnaire. **AQ–Anx** = Acrophobia Questionnaire, Anxiety subscale. Participants completed the questions related to individual characteristics and the ITQ at pre only. Participants completed the AQ and the BSQ at post only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
*$p < .05$. **$p < .01$.

Shoulder rotations

Prior to performing the inferential analyses presented in the main text, the distribution of shoulder rotation angles in each experimental condition were visually inspected (see Figure 7).

Figure 7 Distribution of participants' shoulder rotation angles in each experimental condition

(A) Control condition

(B) Risk of falling condition

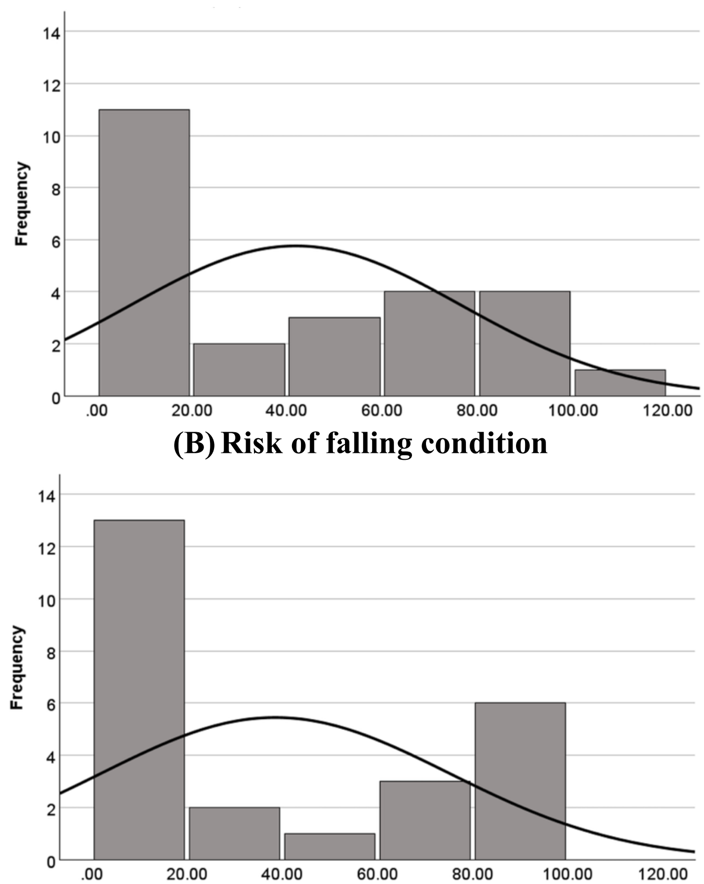
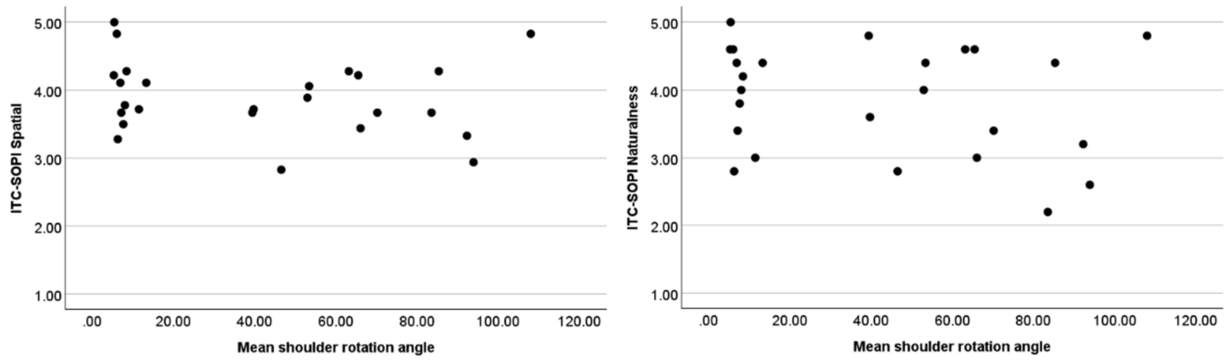


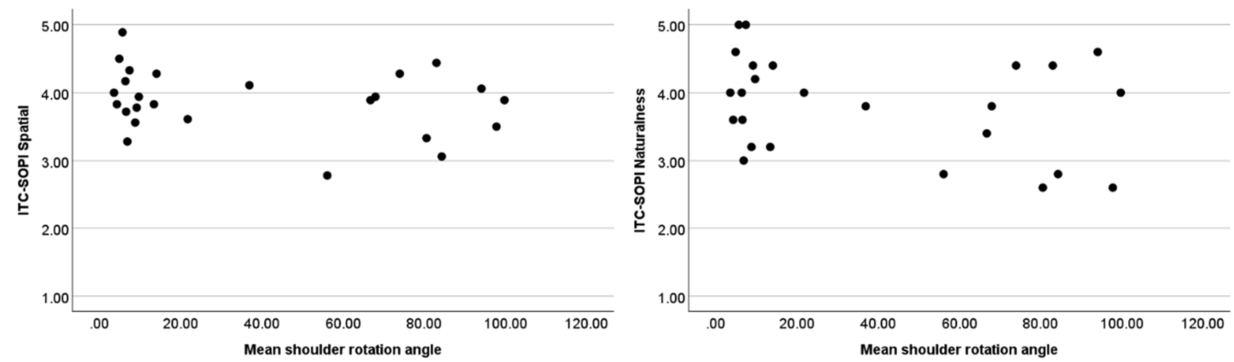
Figure 8 for scatterplots presents scatterplots of shoulder rotation angles and self-report measures of presence within each experimental condition.

Figure 8 Correlations between participants' mean shoulder rotations and ITC-SOPI Spatial Presence and Naturalness subscales in each experimental condition

(A) Control condition



(B) Risk of falling condition



Exploratory analyses were conducted to examine whether the dichotomous measure of rotating the shoulders would be correlated with the self-report measure of anxiety (STAI), presence (shoulder rotations and ITC-SOPI subscales), or cybersickness (SSQ-Raw). To do so, the participants were first manually classified into one of two groups: (1) Did not rotate shoulders (coded as 0) for participants with a mean shoulder rotation angle below 35°; or (2) Rotated shoulders (coded as 1) for participants with a mean shoulder rotation angle equal or above 35° (see Table 10 for descriptive statistics). Then, point-biserial correlations (equivalent to Pearson's r) were performed with this new dichotomous variable and the STAI, the ITC-SOPI, and the SSQ-Raw (see Table 11). The results were not statistically significant, regardless of whether the Holm-Bonferroni correction was applied. Furthermore, raw SSQ scores (SSQ-Raw) were used to facilitate comparisons across studies.

Table 10 Descriptive statistics of shoulder rotation angles and questionnaire scores for the dichotomous measure of shoulder rotation (Did not rotate shoulders versus Rotated shoulders) per experimental condition

Group and Variable	*M*	*Mdn*	*SD*	Minimum	Maximum
Did not rotate shoulders					
Control (*n* = 11)					
Shoulder Rotation Angle	7.83	7.15	2.51	5.30	13.30
STAI	28.27	26.00	6.29	20.00	37.00
ITC-SOPI–Spatial	4.05	4.11	.53	3.28	5.00
ITC-SOPI–Engagement	3.73	3.46	.49	3.15	4.62
ITC-SOPI–Naturalness	4.02	4.20	.70	2.80	5.00
ITC-SOPI–Neg. Effects	1.65	1.50	.42	1.00	2.33
SSQ–Nausea-Raw	.73	1.00	.79	.00	2.00
SSQ–Oculomotor-Raw	1.18	1.00	1.60	.00	5.00
SSQ–Total-Raw	1.91	1.00	2.12	.00	6.00
Risk of falling (*n* = 14)					
Shoulder Rotation Angle	8.76	7.15	4.85	3.59	21.74
STAI	31.36	31.00	6.89	21.00	46.00
ITC-SOPI–Spatial	3.98	3.89	.42	3.28	4.89
ITC-SOPI–Engagement	3.76	3.74	.47	3.08	4.69
ITC-SOPI–Naturalness	4.01	4.00	.64	3.00	5.00
ITC-SOPI–Neg. Effects	1.74	1.59	.67	1.00	3.17
SSQ–Nausea-Raw	.57	.00	.76	.00	2.00
SSQ–Oculomotor-Raw	1.93	1.00	3.00	.00	11.00
SSQ–Total-Raw	2.50	1.00	3.37	.00	12.00
Rotated shoulders					
Control (*n* = 14)					
Shoulder Rotation Angle	68.61	65.82	21.40	39.44	108.04
STAI	26.71	25.50	6.22	20.00	38.00
ITC-SOPI–Spatial	3.77	3.70	.54	2.83	4.83
ITC-SOPI–Engagement	3.62	3.66	.54	2.69	4.54
ITC-SOPI–Naturalness	3.74	3.80	.89	2.20	4.80
ITC-SOPI–Neg. Effects	1.46	1.17	.62	1.00	2.67
SSQ–Nausea-Raw	.43	.00	.76	.00	2.00
SSQ–Oculomotor-Raw	1.71	.00	3.22	.00	11.00
SSQ–Total-Raw	2.14	.00	3.90	.00	13.00
Risk of falling (*n* = 11)					
Shoulder Rotation Angle	76.52	80.59	18.92	36.96	99.80
STAI	26.00	23.00	6.81	20.00	39.00
ITC-SOPI–Spatial	3.75	3.89	.52	2.78	4.44
ITC-SOPI–Engagement	3.72	3.85	.57	2.77	4.69
ITC-SOPI–Naturalness	3.56	3.80	.76	2.60	4.60
ITC-SOPI–Neg. Effects	1.55	1.17	.66	1.00	2.67
SSQ–Nausea-Raw	.36	.00	.92	.00	3.00
SSQ–Oculomotor-Raw	.91	.00	1.58	.00	5.00
SSQ–Total-Raw	1.27	.00	2.41	.00	8.00

Table 11 Point-biserial correlations between the dichotomous measure of shoulder rotation (Did not rotate shoulders versus Rotated shoulders), anxiety, presence, and cybersickness (n = 25)

Variable	Control Rotated Shoulders	Risk of falling Rotated Shoulders
STAI	-.13	-.37
ITC-SOPI–Spatial	-.25	-.24
ITC-SOPI–Engagement	-.11	-.04
ITC-SOPI–Naturalness	-.17	-.32
ITC-SOPI–Neg. Effects	-.17	-.15
SSQ–Nausea-Raw	-.20	-.13
SSQ–Oculomotor-Raw	.10	-.21
SSQ–Total-Raw	.04	-.21

In addition, independent-samples t-tests and Mann-Whitney U tests were conducted to explore whether the groups (Did not rotate versus Rotated) significantly differed in terms of self-reported anxiety, presence, or cybersickness (see Table 12). Levene's test for equality of variances was not statistically significant. Thus, equal variances were assumed for the t-tests. The results of the t-tests and Mann-Whitney U tests were not statistically significant, regardless of whether the Holm-Bonferroni correction was applied.

Table 12 Results from independent-samples t-tests (two-sided p, equal variances assumed) and Mann-Whitney U tests by experimental condition

Variable	Control			Risk of falling		
	t	*df*	*p*	*t*	*df*	*p*
STAI	.62	23	.542	1.94	23	.065
ITC-SOPI–Spatial	1.25	23	.223	1.21	23	.239
ITC-SOPI–Engagement	.51	23	.616	.20	23	.845
ITC-SOPI–Naturalness	.84	23	.408	1.61	23	.122
ITC-SOPI–Neg. Effects	.85	23	.403	.72	23	.479
SSQ–Nausea-Raw	.96	23	.345	.62	23	.542
SSQ–Oculomotor-Raw	-.50	23	.622	1.02	23	.319
SSQ–Total-Raw	-.18	23	.860	1.02	23	.319

	Control		Risk of falling	
	U	*p*	*U*	*p*
STAI	64.50	.492	42.00	.054
ITC-SOPI–Spatial	57.00	.272	64.00	.476
ITC-SOPI–Engagement	70.50	.721	74.00	.869
ITC-SOPI–Naturalness	66.00	.545	51.00	.152

ITC-SOPI–Neg. Effects	51.00	.149	58.50	.305
SSQ–Nausea-Raw	59.00	.261	60.00	.258
SSQ–Oculomotor-Raw	69.50	.650	60.50	.328
SSQ–Total-Raw	63.50	.425	56.50	.225

Note. **Control** condition: *n* = 11 did not rotate shoulders and *n* = 14 rotated shoulders; **Risk of falling** condition: *n* = 14 did not rotate shoulders and *n* = 11 rotated shoulders.

Cybersickness

First, descriptive statistics using the corrected SSQ scores (SSQ-Anx) were calculated (see Table 13 and Table 14). The descriptive statistics for the raw SSQ scores (SSQ-Raw) are reported within the main article. Two sets of Spearman correlations were then performed. The first set (see Table 15) examined the relationship between anxiety (STAI), presence (ITC-SOPI), cybersickness (SSQ-Anx and ITC-SOPI–Negative Effects), and shoulder rotation angles within each experimental condition. The second set (see Table 16) explored the relationship between cybersickness (SSQ-Anx), postural stability (COP parameters), and motion sickness (MSSQ) across time. Several correlations within measures were statistically significant, even after applying the Holm-Bonferroni correction.

Table 13 Descriptive statistics of corrected SSQ scores per experimental condition ($n = 25$)

Variable	Control			Risk of falling		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*
SSQ–Nausea-Anx	.48	.00	.71	.40	.00	.65
SSQ–Oculomotor-Anx	1.32	.00	2.34	1.20	.00	2.04
SSQ–Total-Anx	1.80	.00	2.89	1.60	.00	2.45

Table 14 Descriptive statistics of corrected SSQ scores per immersion (time) ($n = 25$)

Variable	Pre			Immersion 1			Immersion 2		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*	*M*	*Mdn*	*SD*
SSQ–Nausea-Anx	1.68	.00	3.74	.44	.00	.77	.44	.00	.58
SSQ–Oculomotor-Anx	2.28	1.00	2.76	1.16	.00	2.19	1.36	.00	2.20
SSQ–Total-Anx	3.96	2.00	6.34	1.60	.00	2.75	1.80	1.00	2.60

Note. **Pre** = Before the first immersion; **Immersion 1** = After the first immersion; **Immersion 2** = After the last (second) immersion.

Table 15 Spearman correlations between shoulder rotation angles, anxiety, presence, and cybersickness by experimental condition (SSQ excludes items related to anxiety, i.e., items 1 and 9)

Condition and Variable	1	2	3	4	5	6	7	8	9
Control									
1. Shoulder Rotation Angle	–								
2. STAI	-.30	–							
3. ITC-SOPI–Spatial	-.21	-.14	–						
4. ITC-SOPI–Engagement	-.15	-.02	**.59****	–					
5. ITC-SOPI–Naturalness	-.25	-.01	**.82****	**.62****	–				
6. ITC-SOPI–Neg. Effects	-.30	**.65****	.22	.08	.17	–			
7. SSQ–Nausea-Anx	-.20	**.52****	.06	.02	.20	**.54****	–		
8. SSQ–Oculomotor-Anx	-.15	**.56****	.18	.04	.32	**.66****	**.76****	–	
9. SSQ–Total-Anx	-.21	**.63****	.12	.08	.26	**.67****	**.88****	**.96****	–
Risk of falling									
1. Shoulder Rotation Angle	–								
2. STAI	-.24	–							
3. ITC-SOPI–Spatial	-.23	-.01	–						
4. ITC-SOPI–Engagement	-.09	.08	**.71****	–					
5. ITC-SOPI–Naturalness	-.24	.14	**.86****	**.74****	–				
6. ITC-SOPI–Neg. Effects	-.16	**.51****	.30	.28	.31	–			
7. SSQ–Nausea-Anx	-.20	**.69****	.04	.07	.14	**.48***	–		
8. SSQ–Oculomotor-Anx	-.09	**.58****	-.18	-.18	-.06	.38	**.74****	–	
9. SSQ–Total-Anx	-.11	**.63****	-.15	-.14	-.03	**.42***	**.82****	**.99****	–

Note. **Control** condition: $n = 25$; **Risk of falling** condition: $n = 25$.
*$p < .05$. **$p < .01$.

Table 16 Spearman correlations between cybersickness, postural stability, and motion sickness by immersion (time)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. SSQ–Nausea-Anx (Imm. 1)	–												
2. SSQ–Oculomotor-Anx (Imm. 1)	**.75****	–											
3. SSQ–Total-Anx (Imm. 1)	**.81****	**.99****	–										
4. SSQ–Nausea-Anx (Imm. 2)	**.75****	**.80****	**.81****	–									
5. SSQ–Oculomotor-Anx (Imm. 2)	**.50***	**.64****	**.64****	**.75****	–								
6. SSQ–Total-Anx (Imm. 2)	**.64****	**.74****	**.75****	**.88****	**.96****	–							
7. EO–Ellipse (Pre)	.16	.31	.29	.05	.11	.12	–						
8. EO–Velocity (Pre)	.08	-.13	-.12	.11	-.01	.02	-.19	–					
9. EC–Ellipse (Pre)	.26	.20	.24	.06	-.06	.00	**.56****	-.15	–				
10. EC–Velocity (Pre)	-.34	-.36	-.39	-.12	-.08	-.12	-.33	**.72****	-.25	–			
11. MSSQ–Child (Pre)	.26	.10	.12	.17	.25	.20	-.02	-.07	-.20	-.25	–		
12. MSSQ–Adult (Pre)	.25	.17	.17	.02	.10	.05	.31	-.15	.02	-.35	**.77****	–	
13. MSSQ–Total (Pre)	.22	.11	.12	.09	.18	.13	.08	-.17	-.16	-.32	**.96****	**.88****	–

Note. **Pre** = Before the first immersion ($n = 25$); **Immersion 1** = After the first immersion ($n = 25$); **Immersion 2** = After the last (second) immersion ($n = 25$). SSQ excludes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
*$p < .05$. **$p < .01$.

To explore whether cybersickness (SSQ-Raw) after the immersions was related to motion sickness (MSSQ) and postural stability (COP parameters), participants were classified into one of two groups: (1) No cybersickness (coded as 0); or (2) Cybersickness (coded as 1) (similar to Arcioni et al., 2019; Litleskare, 2021; Risi & Palmisano, 2019; Teixeira et al., 2025). First, a grand total SSQ-Raw post-immersion score was calculated for each participant (i.e., the sum of the total SSQ-Raw scores after each immersion). Participants were then manually classified based on the grand total score: (1) No cybersickness for participants with a grand total SSQ-Raw score equal to 0; or (2) Cybersickness for participants with a grand total SSQ-Raw score greater than 0 (see Table 17 for descriptive statistics). Raw SSQ scores (SSQ-Raw) were used to facilitate comparisons between studies.

Following the classification, exploratory independent-samples t-tests and Mann-Whitney U tests were conducted to examine whether the MSSQ and the COP parameters significantly differed between the "No cybersickness" and "Cybersickness" groups (see Table 18). Levene's test for equality of variances was statistically significant for some COP parameters (the test was not significant for other variables). Thus, equal variances were not assumed for the t-tests with the affected COP parameters. Only the t-test and the Mann-Whitney U test with the 95% confidence ellipse area after the second immersion was statistically significant. However, they were no longer significant after applying the Holm-Bonferroni correction.

Table 17 Descriptive statistics of questionnaire scores and postural stability for the cybersickness groups (No cybersickness versus Cybersickness) per immersion (time)

Group and Variable	Pre			Immersion 1			Immersion 2		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*	*M*	*Mdn*	*SD*
No cybersickness (*n* =11)									
SSQ–Nausea-Raw	.55	.00	1.21	.00	.00	.00	.00	.00	.00
SSQ–Oculomotor-Raw	1.00	1.00	1.34	.00	.00	.00	.00	.00	.00
SSQ–Total-Raw	1.55	1.00	2.38	.00	.00	.00	.00	.00	.00
EO–Ellipse	91.76	53.42	73.48	171.39	78.55	219.25	111.91	79.28	62.70
EO–Velocity	6.07	6.38	1.48	6.29	6.11	1.57	6.60	6.40	1.78
EC–Ellipse	120.28	89.44	76.31	159.51	90.58	181.12	112.52	94.40	71.02
EC–Velocity	8.59	8.51	1.22	7.97	8.12	1.54	8.18	8.12	2.13
MSSQ–Child	4.72	4.00	4.15	–	–	–	–	–	–
MSSQ–Adult	3.26	2.25	4.22	–	–	–	–	–	–
MSSQ–Total	7.98	5.40	8.09	–	–	–	–	–	–
Cybersickness (*n* =14)									
SSQ–Nausea-Raw	3.21	1.00	5.24	.86	.50	1.03	1.00	1.00	.68
SSQ–Oculomotor-Raw	3.93	2.50	3.83	2.50	2.00	2.90	2.79	1.50	2.97
SSQ–Total-Raw	7.14	3.50	8.92	3.36	2.50	3.59	3.79	2.50	3.19
EO–Ellipse	110.43	107.43	47.17	158.55	163.52	65.19	149.09	127.42	87.39
EO–Velocity	6.09	5.45	1.84	6.64	6.27	1.83	6.04	5.97	1.06
EC–Ellipse	153.93	102.49	132.19	225.66	135.69	241.66	196.93	186.20	113.83
EC–Velocity	7.90	8.10	2.18	8.00	7.12	2.91	7.40	7.26	2.06
MSSQ–Child	5.15	2.93	5.36	–	–	–	–	–	–
MSSQ–Adult	4.22	1.50	4.95	–	–	–	–	–	–
MSSQ–Total	9.37	3.86	10.02	–	–	–	–	–	–

Note. **Pre** = Before the first immersion (*n* = 25 for questionnaires and *n* = 25 for postural stability data); **Immersion 1** = After the first immersion (*n* = 25 for questionnaires and *n* = 24 for postural stability data with eyes open, *n* = 25 with eyes closed); **Immersion 2** = After the last (second) immersion (*n* = 25 for questionnaires and *n* = 25 for postural stability data). SSQ includes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).

Table 18 Results from independent-samples t-tests (two-sided *p*, equal variances assumed except for some COP parameters) and Mann-Whitney U tests by immersion (time)

Variable	Pre			Immersion 1			Immersion 2		
	t	*df*	*p*	*t*	*df*	*p*	*t*	*df*	*p*
EO–Ellipse	-.77	23	.448	.18	10.14	.861	-1.19	23	.247
EO–Velocity	-.03	23	.974	-.48	22	.636	.93	15.37	.366
EC–Ellipse	-.75	23	.461	-.76	23	.458	-2.15	23	**.043***
EC–Velocity	.94	23	.359	-.02	20.54	.980	.93	23	.364
MSSQ–Child	-.22	23	.832	–	–	–	–	–	–
MSSQ–Adult	-.52	23	.611	–	–	–	–	–	–
MSSQ–Total	-.37	23	.712	–	–	–	–	–	–

	Pre		Immersion 1		Immersion 2	
	U	*p*	*U*	*p*	*U*	*p*
EO–Ellipse	51.00	.155	41.00	.089	58.00	.298
EO–Velocity	72.00	.784	66.00	.815	63.00	.443
EC–Ellipse	63.00	.443	59.00	.324	35.00	**.021***
EC–Velocity	59.00	.324	67.00	.584	58.00	.298
MSSQ–Child	76.00	.956	–	–	–	–
MSSQ–Adult	72.00	.777	–	–	–	–
MSSQ–Total	75.50	.934	–	–	–	–

Note. **Pre** = Before the first immersion ($n = 25$ for questionnaires and $n = 25$ for postural stability data); **Immersion 1** = After the first immersion ($n = 25$ for questionnaires and $n = 24$ for postural stability data with eyes open, $n = 25$ with eyes closed); **Immersion 2** = After the last (second) immersion ($n = 25$ for questionnaires and $n = 25$ for postural stability data). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
*$p < .05$.

Postural stability

To explore the potential impact of sensory dominance (visual versus proprioceptive) on postural stability (COP parameters), cybersickness (SSQ-Raw), and motion sickness (MSSQ), the Romberg quotient (RQ) was calculated for each participant (see Cornilleau-Pérès et al., 2005; Kelly et al., 2008; and Palmisano et al., 2014 for additional details on the calculation procedure):

$$RQ = x(EC)/x(EO)$$

where χ represents the COP parameter measured during the trial, *EC* represents the eyes closed trial, and *EO* represents the eyes open trial.

Specifically, the RQ for mean COP velocity was calculated for each participant, as it has been considered a reliable COP parameter across trials (Cornilleau-Pérès et al., 2005; Duarte & Freitas, 2010; Paillard & Noé, 2015):

$$RQ = vel(EC)/vel(EO)$$

Based on the RQ for mean COP velocity, participants were manually classified into one of two groups: (1) “Visual dominance” (coded as 1) for participants with a RQ greater than 1; or (2) “Proprioceptive dominance” (coded as 2) for participants with a RQ less than or equal to 1 (see Table 19 for descriptive statistics). Raw SSQ scores (SSQ-Raw) were used to facilitate comparisons between studies.

Table 19 Descriptive statistics of questionnaire scores and postural stability for the sensory dominance groups (Visual dominance versus Proprioceptive dominance) per immersion (time)

Group and Variable	Pre (n_{visual} = 23; $n_{proprio}$ = 2)			Immersion 1 (n_{visual} = 19; $n_{proprio}$ = 5)			Immersion 2 (n_{visual} = 20; $n_{proprio}$ = 5)		
	M	*Mdn*	*SD*	*M*	*Mdn*	*SD*	*M*	*Mdn*	*SD*
Visual dominance									
SSQ–Nausea-Raw	1.52	.00	3.48	.42	.00	.84	.60	.00	.75
SSQ–Oculomotor-Raw	2.22	1.00	2.78	1.47	.00	2.74	1.70	1.00	2.72
SSQ–Total-Raw	3.74	2.00	6.06	1.89	.00	3.40	2.30	1.50	3.16
EO–Ellipse	102.42	75.14	62.06	173.52	108.43	159.33	134.39	98.89	83.95
EO–Velocity	6.17	5.70	1.66	6.21	5.94	1.45	6.24	6.19	1.40
EC–Ellipse	138.26	93.83	113.56	167.12	96.72	169.05	151.24	102.15	105.66
EC–Velocity	8.49	8.51	1.56	8.27	7.90	2.42	8.33	7.99	1.85
MSSQ–Child	4.29	3.86	4.35	–	–	–	–	–	–
MSSQ–Adult	3.25	1.00	4.36	–	–	–	–	–	–
MSSQ–Total	7.54	4.00	8.39	–	–	–	–	–	–
Proprioceptive dominance									
SSQ–Nausea-Raw	8.00	8.00	8.49	.80	.00	1.10	.40	.00	.55
SSQ–Oculomotor-Raw	7.50	7.50	6.36	1.40	1.00	1.67	1.00	.00	2.24
SSQ–Total-Raw	15.50	15.50	14.85	2.20	2.00	2.49	1.40	.00	2.61
EO–Ellipse	99.91	99.91	17.90	127.37	142.48	76.56	126.10	128.18	56.81
EO–Velocity	5.11	5.11	1.77	7.54	6.44	2.34	6.45	6.06	1.65
EC–Ellipse	149.07	149.07	91.94	294.58	152.53	364.16	193.97	177.17	104.09
EC–Velocity	4.96	4.96	1.72	6.90	6.27	2.31	5.40	5.26	1.15
MSSQ–Child	12.69	12.69	.44	–	–	–	–	–	–
MSSQ–Adult	10.07	10.07	.09	–	–	–	–	–	–
MSSQ–Total	22.75	22.75	.35	–	–	–	–	–	–

Note. **Pre** = Before the first immersion (n = 25 for questionnaires and n = 25 for postural stability data); **Immersion 1** = After the first immersion (n = 25 for questionnaires and n = 24 for postural stability data with eyes open, n = 25 with eyes closed); **Immersion 2** = After the last (second) immersion (n = 25 for questionnaires and n = 25 for postural stability data). SSQ includes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).

Exploratory independent-samples t-tests and Mann-Whitney U tests were performed to investigate whether the “Visual” and “Proprioceptive” groups significantly differed in terms of COP parameters, SSQ-Raw, and MSSQ (see Table 20). The results showed that most of the variables before the first immersion, and the COP parameters after the second immersion statistically significantly differed between the groups. Levene’s test for equality of variances was not statistically significant. Thus, equal variances were assumed for the t-tests. While most of the t-tests remained significant after applying the Holm-Bonferroni correction, the Mann-Whitney U tests did not, except after the second immersion. This suggests that the results of the t-tests may have been obtained by chance. However, it seems that the postural stability of participants differed during the trials with eyes closed depending on whether they had visual or proprioceptive dominance. Further work is needed to assess the relationship between postural stability and sensory dominance, since the groups were small and did not significantly differ at all timepoints, and postural stability was not continuously measured during the study.

Table 20 Results from independent-samples t-tests (two-sided *p*, equal variances assumed) and Mann-Whitney U tests by immersion (time)

Variable	Pre			Immersion 1			Immersion 2		
	t	*df*	*p*	*t*	*df*	*p*	*t*	*df*	*p*
SSQ–Nausea-Raw	-2.29	23	**.031***	-.85	22	.406	.55	23	.585
SSQ–Oculomotor-Raw	-2.37	23	**.027***	.06	22	.955	.53	23	.601
SSQ–Total-Raw	-2.39	23	**.026***	-.19	22	.854	.59	23	.564
EO–Ellipse	.06	23	.956	.62	22	.541	.21	23	.837
EO–Velocity	.86	23	.396	-1.61	22	.123	-.28	23	.781
EC–Ellipse	-.13	23	.898	-1.16	22	.257	-.81	23	.426
EC–Velocity	3.05	23	**.006****	1.13	22	.270	3.35	23	**.003****
MSSQ–Child	-2.68	23	**.013***	–	–	–	–	–	–
MSSQ–Adult	-2.17	23	**.041***	–	–	–	–	–	–
MSSQ–Total	-2.52	23	**.019***	–	–	–	–	–	–

	Pre		Immersion 1		Immersion 2	
	U	*p*	*U*	*p*	*U*	*p*
SSQ–Nausea-Raw	4.50	**.047***	39.00	.451	44.50	.674
SSQ–Oculomotor-Raw	5.50	.074	41.00	.613	36.00	.302
SSQ–Total-Raw	4.50	.061	39.00	.509	40.50	.493
EO–Ellipse	19.00	.689	42.00	.696	45.00	.734
EO–Velocity	14.00	.367	31.00	.241	47.50	.865
EC–Ellipse	20.00	.764	35.00	.374	34.00	.277
EC–Velocity	2.00	**.035***	33.00	.303	9.00	**.005****
MSSQ–Child	2.00	**.034***	–	–	–	–
MSSQ–Adult	6.00	.078	–	–	–	–
MSSQ–Total	3.50	.050	–	–	–	–

Note. **Pre** = Before the first immersion (n = 25 for questionnaires and n = 25 for postural stability data); **Immersion 1** = After the first immersion (n = 25 for questionnaires and n = 24 for postural stability data with eyes open, n = 25 with eyes closed); **Immersion 2** = After the last (second) immersion (n = 25 for questionnaires and n = 25 for postural stability data). SSQ includes items related to anxiety (i.e., items 1 and 9). Participants completed the MSSQ at pre only. Postural stability test: **EO–Ellipse** = Trial with eyes open, 95% confidence ellipse area (mm^2); **EO–Velocity** = Trial with eyes open, mean COP velocity (mm/s); **EC–Ellipse** = Trial with eyes closed, 95% confidence ellipse area (mm^2); **EC–Velocity** = Trial with eyes closed, mean COP velocity (mm/s).
$^*p < .05$. $^{**}p < .01$.

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Chapitre 6 : Discussion générale

Globalement, l'objectif de la thèse était d'évaluer une mesure comportementale de la présence en RV et de documenter la convergence entre les mesures subjectives et objectives de la présence. La thèse comprend un article sur un modèle conceptuel de la présence (Chapitre 2), ainsi que deux études expérimentales (Chapitre 4 et Chapitre 5). L'article sur le modèle conceptuel de la présence (Chapitre 2) a examiné le rôle de l'intégration multisensorielle sur la présence, ainsi que les relations entre l'émotion et la présence, et entre la présence et le comportement. Les deux études expérimentales (Chapitre 4 et Chapitre 5) ont exploré la relation entre des variables discutées dans le modèle (p. ex., émotion, stimulation multisensorielle), ainsi qu'entre deux mesures de la présence (auto-rapportée et comportementale) dans un contexte d'anxiété. Les prochaines sections résument le modèle conceptuel et les résultats communs entre les deux études et leurs implications.

L'article sur le modèle conceptuel de la présence (Chapitre 2) a été publié en 2018 (Berthiaume et al., 2018) et a été cité par des articles portant sur des sujets variés, tels que l'incarnation virtuelle (*virtual embodiment*), le mal des transports, la conscience situationnelle (*situational awareness*), etc. Le modèle propose que l'intégration multisensorielle joue un rôle important sur la présence et les émotions en RV. Il discute également de l'illusion de plausibilité et l'illusion de place et propose que la crédibilité de l'environnement virtuel contribue aux deux illusions. Bien que l'article ait été publié il y a quelques années, il est toujours pertinent à l'expérience des utilisateurs en RV. D'autres modèles conceptuels qui discutent de l'illusion de place et l'illusion de plausibilité ont été publiés depuis 2018, tels que ceux proposés par Hofer et al. (2020), Latoschik et Wienrich (2022) et Hameed et Perkis (2024). Hofer et al. (2020) ont présenté une approche à deux systèmes (*dual-systems approach*). Les auteurs ont postulé que la présence est un processus cognitif de bas niveau (*lower-order cognitive process*), qui pourrait être influencée par des processus cognitifs de haut niveau (*higher-order cognitive processes*), tels que la perception d'une violation de la plausibilité. Le modèle conceptuel de la présence présenté dans la thèse a plutôt proposé que l'illusion de plausibilité est un processus cognitif de bas niveau et l'illusion de place est un processus cognitif de haut niveau.

Le modèle de Hameed et Perkis (2024) se concentre sur l'évaluation de la qualité de l'expérience en RV. Les auteurs ont proposé deux composantes de l'expérience en RV : la présence et l'authenticité (*authenticity*). L'authenticité est divisée en deux caractéristiques : la plausibilité (*plausibility*) et la crédibilité (*believability*). La plausibilité réfère à la congruence ou la fidélité de l'environnement virtuel avec l'environnement physique. Quant à elle, la crédibilité désigne la cohérence/logique interne de l'environnement virtuel. Le modèle conceptuel dans la thèse utilise une terminologie semblable, mais la relation entre les concepts diffère. Par exemple, ce dernier utilise également le terme « congruence », qui réfère au niveau de fidélité de l'environnement virtuel avec l'environnement physique. De plus, il utilise le terme « crédibilité » (*believability*), qui désigne la cohérence/logique interne de l'environnement virtuel. Cependant, il conserve le cadre conceptuel de Slater, où la présence est divisée en illusion de place et illusion de plausibilité (plutôt qu'en présence et authenticité).

Le modèle de Latoschik et Wienrich (2022) ne sera pas discuté, car il se concentre sur la réalité étendue (*extended reality, ou XR*), qui est au-delà du cadre de la thèse. D'autre part, Slater et al. (2022) ont mis à jour leur modèle sur l'illusion de place et l'illusion de plausibilité afin d'inclure la co-présence (une composante de la présence sociale), des méthodes pour mesurer les deux illusions et des directions pour la recherche future. Puisque les définitions des deux illusions demeurent inchangées, le modèle ne sera pas discuté. Bref, le modèle conceptuel de la présence dans la thèse semble, dans l'ensemble, toujours être aligné avec les publications plus récentes.

L'objectif principal des deux études expérimentales de la thèse (Chapitre 4 et Chapitre 5) était de mieux comprendre la relation entre la présence auto-rapportée et le comportement. Les deux études ont également examiné la relation entre des variables discutées dans le modèle conceptuel (Chapitre 2), telles que la présence, l'anxiété et la stimulation multisensorielle. Spécifiquement, une mesure comportementale de la présence a été utilisée, qui implique que les participants pivotent physiquement les épaules pour passer dans des portes virtuelles étroites. Les études par Lepecq et al. (2009) et Mestre et al. (2016) ont inspiré cette mesure. Afin d'induire de l'anxiété, les participants ont marché sur une planche virtuelle (avec une planche physique correspondante dans le laboratoire) et ont été exposés à une fosse profonde virtuelle.

Dans la première étude expérimentale (Chapitre 4), la méthodologie a été évaluée afin de valider les environnements virtuels et le paradigme des portes virtuelles en contexte émotionnel. Plus précisément, l'étude a examiné la relation entre les mesures auto-rapportées et comportementales de la présence, ainsi qu'entre la présence et l'anxiété. Les principales hypothèses étaient que les mesures auto-rapportées et comportementales de la présence, ainsi que la présence et l'anxiété, seraient corrélées et que l'anxiété serait plus élevée dans la condition avec le risque de tomber. Les résultats n'ont pas confirmé les hypothèses. Cependant, les résultats ont révélé une corrélation statistiquement significative entre l'anxiété et les cybermalaises.

La deuxième étude expérimentale (Chapitre 5), une réplication bonifiée, a apporté des modifications au protocole expérimental et à l'environnement virtuel afin d'augmenter la présence (p. ex., ajout du retour haptique lorsque les participants entraient en collision avec les portes virtuelles) et l'anxiété (p. ex., retrait de piliers autour de la planche virtuelle). La condition Risque de tomber + Feu a également été retirée. Autrement dit, la deuxième étude a seulement exposé les participants aux conditions Contrôle et Risque de tomber. Après avoir apporté les modifications, l'étude a exploré la relation entre les mesures auto-rapportées et comportementales de la présence, l'anxiété, la stimulation multisensorielle et les cybermalaises. Les principales hypothèses mises de l'avant étaient identiques à la première étude. Toutefois, à la suite des résultats liés aux cybermalaises de la première étude, la deuxième a également émis l'hypothèse que la présence et les cybermalaises, ainsi que l'anxiété et les cybermalaises, seraient corrélés. Les résultats étaient semblables à ceux de la première étude. Spécifiquement, la corrélation entre les mesures auto-rapportées et comportementales de la présence, ainsi qu'entre la présence et l'anxiété n'était pas statistiquement significative. D'autre part, la corrélation entre les cybermalaises et la stabilité posturale, ainsi qu'entre l'anxiété et la stabilité posturale n'était pas significative. De plus, l'anxiété n'a pas différé de manière significative entre les conditions expérimentales. Cependant, la corrélation entre l'anxiété et les cybermalaises était statistiquement significative.

Dans les deux études, les participants ont physiquement pivoté les épaules pour passer dans les portes virtuelles étroites, quoique l'amplitude de rotation moyenne (en degrés) était plus petite dans la deuxième étude que la première. La différence entre les études pourrait s'expliquer par des différences méthodologiques (p. ex., aucun retour haptique versus ajout de retour haptique). Dans les deux études, certains participants ont également comprimé leurs épaules ou utilisé leurs mains pour toucher ou ouvrir les portes, qui étaient des comportements inattendus. Il est possible que les possibilités d'action soient plus évidentes dans l'environnement physique que dans un environnement virtuel. Il se peut également que ces comportements correspondent au comportement habituel des participants dans l'environnement physique. Par exemple, les deux études expérimentales ont supposé que le comportement habituel des participants lorsqu'ils sont confrontés à des ouvertures étroites dans l'environnement physique soit de pivoter les épaules. Toutefois, il est possible que le comportement habituel de certains participants soit de tenter d'ouvrir les portes avec les mains ou de comprimer les épaules, ce qui signifierait que leur comportement en RV est cohérent. Il serait utile dans des études futures de comparer le comportement attendu des participants dans les deux environnements.

D'autre part, dans les deux études, les participants sont entrés en collision avec les portes virtuelles. La fréquence des collisions moyenne était plus élevée dans la deuxième étude que la première. Dans la première étude, la fréquence des collisions était plus élevée dans les conditions Risque de tomber et Risque de tomber + Feu que dans la condition Contrôle. Cependant, dans la deuxième étude, la fréquence des collisions était semblable dans les conditions Contrôle et Risque de tomber. Il est possible que les participants soient entrés en collision avec les portes virtuelles en raison d'une distraction visuelle dans l'environnement virtuel (p. ex., la hauteur et/ou le feu dans la première étude ou le panneau d'avertissement sur les portes dans la deuxième étude). Une erreur de perception ou d'estimation de la « passabilité » des ouvertures (*aperture passability*) aurait pu entraîner des collisions, car l'environnement virtuel n'a pas intégré une représentation visuelle du corps des participants (des détails supplémentaires sont présentés dans la section « Limites des études expérimentales »).

Certains des résultats corroborent ceux de Lepecq et al. (2009) et de Mestre et al. (2016), qui ont inspiré la méthodologie des deux études expérimentales de la thèse. Par exemple, les participants ont physiquement pivoté les épaules dans toutes les études. Toutefois, l'amplitude de rotation moyenne (en degrés) était plus petite et les collisions étaient plus fréquentes dans les deux études de la thèse. Il est possible que la divergence entre les résultats provienne de l’absence d’une représentation visuelle du corps dans les deux études expérimentales de la thèse. En effet, les participants n’étaient peut-être pas conscients de l’emplacement spatial de leurs épaules physiques dans l’environnement virtuel. Dans leur étude, Lepecq et al. (2009) ont immergé les participants dans une voûte, où les participants pouvaient voir leurs épaules physiques. Mestre et al. (2016) ont utilisé un casque de RV, mais ils ont incorporé une représentation visuelle du corps dans l’environnement virtuel. Les études futures impliquant la navigation spatiale ou des jugements spatiaux devraient considérer ajouter un corps virtuel qui est visible aux participants.

Dans les deux études expérimentales de la thèse, la corrélation entre les mesures auto-rapportées et comportementales de la présence n’était pas statistiquement significative. Il est possible que les mesures auto-rapportées et comportementales de la présence ne convergent pas nécessairement. Des études antérieures (p. ex., Brogni et al., 2003) ont montré une corrélation statistiquement significative entre la présence auto-rapportée et les interruptions de la présence (*breaks in presence* ou *BIPs*). Cependant, ces dernières ne constituent pas des mesures comportementales si les participants doivent auto-rapporter lorsqu’ils ne se sentent plus présents (p. ex., verbalement ou à l’aide d’un curseur ; voir Slater & Steed, 2000). Autrement dit, il ne s’agit pas d’un comportement observable dans l’environnement virtuel. Une comparaison directe entre les corrélations présence-interruptions et présence-comportement pourrait donc être difficile, car celles-ci ne sont peut-être pas équivalentes. Il serait utile que des études futures combinent et comparent d’autres mesures auto-rapportées et comportementales de la présence.

Les scores d’anxiété (IASTA) étaient faibles dans les deux études de la thèse (scores moyens inférieurs à 30 dans toutes les conditions, même les conditions avec le risque de tomber).

Ces résultats sont inférieurs à ceux des études antérieures ayant utilisé des hauteurs virtuelles. Par exemple, dans une étude, Gromer et al. (2018) ont exposé des participants craignant peu les hauteurs (*low height anxious*) et des participants craignant beaucoup les hauteurs (*high height anxious*) à une situation en hauteur en RV. Les résultats ont montré que les scores moyens de l'IASTA après l'immersion étaient 33,29 pour les participants craignant peu les hauteurs et 40,72 pour les participants craignant beaucoup les hauteurs. Dans une autre étude (Felnhofer et al., 2014), des participants avec une anxiété sociale faible et des participants avec une anxiété sociale élevée devaient faire un discours en RV. Les résultats ont indiqué que les scores moyens de l'IASTA après le discours étaient environ 37 pour les participants avec une anxiété sociale faible et environ 48 pour les participants avec une anxiété sociale élevée. La formulation des consignes de l'IASTA dans les études de la thèse pourrait expliquer les scores faibles. Spécifiquement, le questionnaire a évalué l'anxiété dans le moment présent (« […] indiquez comment vous vous sentez <u>maintenant</u>, c'est-à-dire <u>à ce moment précis</u> »[1]) plutôt que pendant l'immersion (« […] indiquez comment vous vous sentiez <u>pendant l'immersion</u> »). Toutefois, le rythme cardiaque a également suggéré une anxiété physiologique semblable entre les conditions expérimentales, ce qui ne soutient pas cette explication.

Les deux études de la thèse ont obtenu une corrélation non significative entre la présence et l'anxiété. Ce résultat est consistant avec certaines études antérieures. Par exemple, des études ont montré une corrélation négative ou non significative (p. ex., Ling et al., 2012 ; Villani et al., 2012) entre les deux variables (p. ex., Bouchard et al., 2008 ; Gromer et al., 2018), mais d'autres ont révélé une corrélation positive (p. ex., Bouchard et al., 2008 ; Gromer et al., 2018). De plus, la première étude expérimentale de la thèse a indiqué une corrélation significative entre la

[1] Cette formulation correspond à celle de la version originale du questionnaire.

présence et certaines sous-échelles des cybermalaises (c.-à-d., Nausée et Oculomoteur). Toutefois, la deuxième étude n'a pas indiqué de corrélation significative entre les deux variables. Des études antérieures ayant examiné la relation entre la présence et les cybermalaises ont obtenu des résultats mitigés (p. ex., Liu & Uang, 2011 ; Weech et al., 2020). Finalement, les deux études de la thèse ont révélé une corrélation significative entre l'anxiété et les cybermalaises. Ce résultat est cohérent avec ceux d'études antérieures (p. ex., Bouchard et al., 2007 ; Bouchard et al., 2009 ; Bouchard et al., 2021). En effet, les symptômes de l'anxiété et des cybermalaises sont semblables (p. ex., inconfort général, difficulté à se concentrer) et peuvent être confondus.

Les deux études expérimentales de la thèse ont permis d'examiner des variables proposées dans le modèle conceptuel de la présence. Par exemple, le modèle stipule que plus le nombre de sens stimulés est élevé, plus l'environnement virtuel ressemble à l'environnement physique. Cependant, les stimuli dans l'environnement virtuel doivent également être congruents avec ceux dans l'environnement physique. Bien que la deuxième étude ait stimulé plus de sens (en ajoutant du retour haptique), cet ajout n'a pas semblé affecter le comportement des participants (c.-à-d., les résultats étaient semblables à la première étude). Il est possible que le manque d'objets physiques correspondants dans les environnements virtuels (à l'exception de la planche en bois) ait influencé la présence auto-rapportée ou le comportement des participants. Spécifiquement, dans l'environnement physique, lorsqu'on entre en collision avec un objet, il y a un retour haptique (p. ex., de la résistance), mais on ressent également l'objet avec lequel on est entré en collision (p. ex., un meuble). En revanche, les environnements virtuels utilisés dans le cadre des deux études contenaient seulement des objets virtuels. En d'autres termes, l'utilisation d'objets virtuels et physiques congruents (p. ex., une structure en bois virtuelle et physique) pourrait mener à une présence plus élevée que l'utilisation d'objets virtuels seulement ou d'objets virtuels et physiques incongruents (p. ex., une structure en bois virtuelle avec du retour haptique, mais aucune structure physique).

Le modèle conceptuel propose également que l'expérience antérieure et les attentes des utilisateurs puissent affecter s'ils trouvent l'environnement virtuel crédible, ce qui aurait ensuite un impact sur la présence. En d'autres termes, si les participants avaient une expérience antérieure (ou pas) et des attentes en lien avec un endroit particulier ou un élément dans l'environnement virtuel, cela aurait pu influencer la crédibilité de l'environnement virtuel et la présence. Par exemple, des participants avaient rapporté trouver le feu virtuel dans la première étude peu réaliste par rapport à un feu dans l'environnement physique (apparence et mouvement). Il est possible que le fait que l'environnement virtuel ne réponde pas aux attentes ait contribué à une présence réduite chez certains participants. Les prochaines sections abordent des limites des deux études expérimentales de la thèse et des directions futures pour la recherche.

Limites des études expérimentales de la thèse

Une limite potentielle de la thèse est que les environnements virtuels ne comprenaient pas un corps virtuel au complet (seulement des mains et des pieds virtuels). Le fait d'avoir un corps virtuel donne un sentiment d'incarnation (*embodiment*) dans l'environnement virtuel (Grabarczyk & Pokropski, 2016) et peut influencer la perception de la taille et de la distance (p. ex., van der Hoort & Ehrsson, 2014). D'autre part, les humains utilisent les repères visuels pour les tâches spatiales, telles que la navigation et les jugements spatiaux (Azevedo, Jorge, & Campos, 2014). Par conséquent, l'absence d'un corps virtuel pourrait avoir un impact négatif sur la navigation dans l'environnement virtuel.

Dans le cadre des deux études expérimentales, l'absence d'un corps virtuel (particulièrement la représentation visuelle des épaules) aurait pu influencer le comportement des participants lorsqu'ils traversaient les portes virtuelles. Cependant, l'objectif n'était pas de traverser les portes sans collision. Il s'agissait plutôt d'observer si les participants tenaient compte des portes (p. ex., en pivotant leurs épaules). Si les participants ne se sentaient pas présents, ils n'auraient pas adopté ce comportement. D'ailleurs, une étude antérieure n'a pas trouvé de différence significative dans les jugements de « passabilité » (*passability judgments*) des portes virtuelles étroites entre la condition avec un avatar et la condition sans avatar (Bhargava, Solini, et al., 2020). Dans les environnements virtuels, les utilisateurs peuvent se sentir présents et heurter des objets en raison d'une altération de la perception des distances en RV ou d'un manque de repères visuels ou haptiques. La présence implique plutôt une tentative d'éviter les collisions avec les objets, car les utilisateurs ont l'impression que les objets sont réellement là.

Le développement d'un avatar représentant l'utilisateur avec un haut niveau de réalisme peut poser un défi important (Bhargava, Lucaites, et al., 2020 ; Bhargava, Solini, et al., 2020), car tout problème technique ou un corps virtuel avec un mouvement non naturel ou qui ne répond pas aux attentes de l'utilisateur pourraient diminuer la présence (Berthiaume et al., 2018). La création d'une grande variété de personnalisations requerrait une grande quantité de ressources et de temps, car cela nécessiterait de mettre en œuvre des animations et de faire correspondre des parties du corps virtuel avec des parties du corps physique, comme le mouvement des articulations, telles que les genoux et les coudes, la longueur des bras et des jambes, etc. Dans une étude, Gonçalves et al. (2021) ont montré que l'ajout de mains et de pieds virtuels peut être suffisant pour améliorer la présence.

Une deuxième limite potentielle est que la capture de mouvement (*mocap*) n'a pas été utilisée dans le cadre de la thèse. L'équipe de recherche a plutôt utilisé un cadre de sac à dos (c.-à-d., un cadre métallique rigide) auquel était fixée une tige métallique rigide qui maintenait les senseurs sur les épaules des participants. Le cadre de sac à dos n'était pas personnalisé à chaque participant (c.-à-d., la longueur et la position de la tige métallique demeurait identique pour tous les participants), mais il était plus étroit que les épaules physiques des participants. Autrement dit, le cadre de sac à dos ne devrait donc pas avoir affecté la manière dont les participants ont pivoté leurs épaules en passant dans les portes virtuelles. La décision d'utiliser le cadre de sac à dos a été prise pour des raisons pratiques. Les études futures pourraient utiliser la capture de mouvement pour évaluer l'amplitude de rotation des épaules et comparer les résultats obtenus avec un cadre de sac à dos.

Une troisième limite est que l'environnement virtuel et l'équipement de RV n'ont pas permis d'évaluer la compression du corps (*body compression*). Plus précisément, les senseurs au-dessus des épaules physiques des participants étaient dans une position fixe. Les deux études expérimentales se sont appuyées sur l'observation, qui est subjective par rapport aux données de mouvement. Les études futures utilisant le paradigme des portes coulissantes virtuelles devraient envisager de se servir de mesures objectives permettant de mesurer la compression du corps, car il est possible que les participants compriment leurs épaules plutôt que de les pivoter (Bhargava et al., 2021; Bhargava et al., 2023).

Finalement, les deux études de la thèse n'ont pas évalué la perception de « passabilité » des portes (*passability judgments*, c.-à-d., si les participants jugeaient pouvoir passer dans les portes virtuelles étroites sans physiquement pivoter les épaules). Noter que Lepecq et al. (2009) et Mestre et al. (2016) ne l'ont pas évaluée non plus. Il est donc incertain si les participants ayant effectué une plus petite rotation des épaules l'ont fait parce qu'ils se sentaient moins présents, parce qu'ils jugeaient pouvoir traverser les portes sans effectuer une grande rotation ou pour une autre raison. Il est également possible que les participants ayant effectué une plus petite rotation des épaules aient effectué une rotation semblable dans l'environnement physique, car leur première réaction est peut-être d'essayer d'ouvrir les portes (c.-à-d., d'élargir l'ouverture) avec leurs mains et ensuite de pivoter les épaules si les portes ne s'ouvraient pas. Ce serait utile dans des études futures de recueillir de la rétroaction des participants sur les raisons qu'ils ont choisi un comportement particulier. Plusieurs études jusqu'à présent semblent avoir soit demandé aux participants de passer dans des portes étroites (p. ex., Lepecq et al., 2009; Mestre et al., 2016) ou de juger s'ils pouvaient passer dans les portes sans ensuite les faires passer dans celles-ci (p. ex., Bhargava, Solini, et al., 2020). Cependant, l'évaluation de la perception de « passabilité » des portes pourrait fournir une perspective plus complète du comportement lié à la traversée des ouvertures étroites (*narrow aperture crossing*) en RV.

Directions futures

Dans les applications de RV qui visent à reproduire un comportement naturel, telles que la formation et la psychothérapie, il est essentiel que les utilisateurs se comportent de manière semblable dans l'environnement virtuel que dans l'environnement physique. Plusieurs études précédentes suggèrent que la présence contribue au comportement des utilisateurs dans l'environnement virtuel (Slater, 2009, 2018 ; Slater et al., 2010, 2022). Il existe de nombreuses méthodes d'améliorer la présence : améliorer le réalisme visuel de l'environnement virtuel, utiliser des méthodes de navigation et d'interaction plus naturelles, ajouter des stimuli multisensoriels, présenter un scénario crédible aux utilisateurs, etc. (voir l'Introduction générale pour une discussion plus détaillée). Toutefois, la ou les méthodes choisies pourraient varier selon le contexte et la tâche.

Par exemple, un réalisme visuel élevé pourrait être plus important pour la chirurgie où la précision est critique pour identifier la partie du corps à opérer et reconnaître les changements pathologiques (Liu et al., 2012) que pour la psychothérapie où un scénario crédible est plus important pour induire une réponse émotionnelle (Baños et al., 2004). D'ailleurs, une étude (Schmied-Kowarzik & Paelke, 2021) a suggéré que le réalisme visuel joue un rôle plus important pour induire la présence chez les participants sans phobie que chez ceux avec une phobie lorsqu'ils sont exposés à un environnement virtuel contenant le stimulus phobogène. En d'autres termes, le contexte et la tâche peuvent orienter le développement des environnements virtuels.

L'amélioration continue du réalisme visuel de l'environnement virtuel n'entraînera pas nécessairement une présence plus élevée, d'autres facteurs pouvant avoir un impact plus important sur cette dernière (Triberti et al., 2025). Par exemple, l'ajout de stimuli multisensoriels pourrait renforcer la présence en augmentant la ressemblance de l'environnement virtuel avec l'environnement physique (Sra, 2023). De plus, la stimulation multisensorielle pourrait être moins dispendieuse et efficace qu'améliorer le réalisme visuel (p. ex., Dinh et al., 1999). Pour les concepteurs d'environnements virtuels, identifier le public cible et l'objectif de l'application pourrait orienter les éléments prioritaires à considérer lors du développement.

Puisque les utilisateurs peuvent faire des comportements inattendus dans l'environnement virtuel, il est utile d'évaluer leur comportement à l'aide de mesures objectives (p. ex., capture de mouvement, enregistrements vidéo). D'autre part, dans le cadre d'études utilisant une mesure comportementale en RV, il pourrait être bénéfique de comparer le comportement des participants dans l'environnement physique et en RV (p. ex., en menant une étude pilote). Cela permettrait de mieux comprendre si le comportement des participants est cohérent dans les deux environnements. De plus, il est utile de tenir compte de l'expérience antérieure et des attentes des utilisateurs, car elles peuvent influencer leur niveau de présence et leur comportement dans l'environnement virtuel. En d'autres termes, si un environnement virtuel ne répond pas à ces attentes, leur présence pourrait être réduite ou leur comportement pourrait ne pas converger avec celui observé dans l'environnement physique.

Dans le même sens, l'utilisation d'une combinaison de mesures de la présence (p. ex., questionnaire, comportement, rétroaction des participants) pourrait aider à mieux comprendre l'expérience des utilisateurs, car les résultats des mesures pourraient ne pas converger. Par exemple, dans une recension systématique, Ernst et al. (2024) ont trouvé un effet semblable entre l'anxiété auto-rapportée et les symptômes physiologiques dans les traitements d'exposition en RV. Dans deux études, Maymon et al. (2024) ont révélé une relation non significative entre la présence auto-rapportée et les mesures physiologiques (rythme cardiaque et conductivité électrique de la peau) lorsque les participants étaient exposés à un environnement virtuel en hauteur. En revanche, la relation entre la présence et l'anxiété auto-rapportées était significative.

Peu d'études antérieures ont utilisé des mesures auto-rapportées et comportementales de la présence dans un contexte d'anxiété. Les deux études expérimentales de la thèse ont administré un questionnaire validé de la présence (ITC-SOPI) et ont évalué le comportement (rotation des épaules). Dans les deux études, les corrélations entre la présence auto-rapportée et le comportement n'étaient pas statistiquement significatives. Ces résultats pourraient s'expliquer par la discordance entre les mesures subjectives et comportementales, un phénomène documenté depuis plusieurs années dans le domaine de l'émotion. Plus précisément, des études antérieures ont révélé que la peur auto-rapportée et le comportement (p. ex., évitement) ne convergent pas nécessairement (p. ex., Benoit Allen et al., 2015 ; Craske & Craig, 1984 ; Hodgson & Rachman, 1974 ; Rachman & Hodgson, 1974). Rachman et Hodgson (1974) ont proposé que la concordance se produise lorsque la peur et l'évitement covarient (c.-à-d., sont corrélés) à un moment donné, alors que la discordance se produit lorsqu'ils ne covarient pas. Rachman et Hodgson ont également introduit les concepts de synchronie et de désynchronie, qui réfèrent plutôt aux changements dans la peur et l'évitement, lesquels peuvent varier de manière conjointe (synchronie) ou de manière indépendante ou inverse (désynchronie).

Dans un deuxième article, Hodgson et Rachman (1974) ont proposé cinq hypothèses, dont une suggérant que la concordance entre les mesures de peur serait plus susceptible de se produire dans des conditions suscitant des réponses émotionnelles intenses, tandis que la discordance serait plus probable dans des conditions suscitant des réponses émotionnelles moins intenses. Les résultats d'une étude (Craske et Craig, 1984), ayant examiné la concordance entre des mesures auto-rapportées et comportementales dans un contexte d'anxiété de performance musicale, ont semblé soutenir partiellement cette hypothèse. Il est possible que, dans les deux études expérimentales de la thèse, la discordance entre les mesures auto-rapportées et comportementales de la présence ait été observée, car les environnements virtuels ont induit un niveau d'anxiété relativement faible chez les participants. Il serait intéressant dans des études futures de recruter des participants avec une phobie des hauteurs et d'examiner la concordance-discordance entre des mesures auto-rapportées et comportementales de la présence lorsqu'ils sont exposés à une situation en hauteur en RV.

Les résultats des deux études de la thèse pourraient avoir des retombées pratiques dans divers domaines qui utilisent la RV, tels que la recherche, la psychothérapie et la formation. Plus précisément, il est possible qu'une concordance entre les mesures auto-rapportées et comportementales de la présence ne soit pas nécessaire pour induire un comportement naturel en RV. Par exemple, dans des environnements virtuels à visées psychothérapeutiques, des clients pourraient rapporter une présence plus faible, mais éviter un objet ou une situation phobogène en RV comme ils le feraient dans l'environnement physique. Parallèlement, des utilisateurs suivant une formation en RV (p. ex., apprendre à répondre à une situation d'urgence) pourraient rapporter une présence plus faible, mais réagir à un incendie virtuel de la même manière que dans l'environnement physique. Il serait utile dans des études futures d'examiner la concordance-discordance entre des mesures auto-rapportées et comportementales de la présence dans d'autres contextes (p. ex., psychothérapie, formation).

Dans les deux études de la thèse, les questionnaires ont été administrés post-immersion dans l'environnement physique (c.-à-d., le laboratoire). Cette méthode présente certains inconvénients. Par exemple, l'administration des questionnaires à l'extérieur de la RV aurait pu avoir un impact sur la présence, car l'expérience en RV a été interrompue. De plus, puisque les participants ont rempli les questionnaires post-immersion, la présence a été mesurée de manière rétrospective. Cependant, il a été décidé de ne pas intégrer les questionnaires dans l'environnement virtuel, car ils étaient relativement longs. Cette méthode a également permis de comparer les résultats avec d'autres études où les participants ont rempli les questionnaires post-immersion dans l'environnement physique (p. ex., Bouchard et al., 2008 ; Felnhofer et al., 2014 ; Gromer et al., 2019 ; Kisker et al., 2021). Il serait utile dans des études futures d'administrer les questionnaires une seule fois dans l'environnement physique à la fin d'une immersion plus longue ou des questionnaires plus courts directement dans l'environnement virtuel. Si les questionnaires sont intégrés dans l'environnement virtuel, cela devrait se faire de manière cohérente avec le scénario. Par exemple, si l'environnement virtuel représente un appartement ou un bureau, les questionnaires pourraient être présentés sur un écran d'ordinateur ou une télévision.

D'autre part, la distinction entre l'anxiété et les cybermalaises est importante dans le cadre des applications de RV qui élicitent l'anxiété à des fins de formation ou de psychothérapie. Il pourrait être utile de continuer à développer des méthodes pour mesurer la présence, l'anxiété et les cybermalaises continuellement pendant les immersions en RV, ce qui permettrait d'évaluer la relation entre ces variables pendant plutôt qu'après les immersions. La recherche future pourrait également continuer à évaluer des mesures et prédicteurs objectifs des cybermalaises. Ceux-ci demeurent un défi pour les casques de RV modernes et la capacité de les prédire pourrait permettre de personnaliser les environnements virtuels et rendre la RV plus confortable et accessible.

Finalement, la deuxième étude expérimentale a évalué la stabilité posturale à l'aide de plateformes de force. Toutefois, la stabilité posturale a seulement été mesurée avant et après les immersions en RV plutôt que continuellement pendant les immersions. La marche physique des participants pendant les immersions n'a pas permis l'évaluation continue de la stabilité posturale, car les plateformes de force exigeaient que les participants restent immobiles. Les études futures devraient mesurer la stabilité posturale de manière continue en RV (p. ex., en utilisant une mesure et/ou une tâche différente).

Chapitre 7 : Conclusion

Un nouveau modèle conceptuel de la présence a exploré le rôle de l'intégration multisensorielle et des émotions sur l'illusion de place, l'illusion de plausibilité et le comportement en RV. Ensuite, deux études expérimentales en RV ont été menées, dont l'objectif principal était d'examiner une mesure comportementale de la présence en contexte d'anxiété, tout en documentant la convergence entre les mesures subjectives et objectives de la présence (première étude expérimentale : $n = 25$; deuxième étude expérimentale : $n = 25$). D'autre part, les deux études ont permis d'examiner des variables présentées dans le modèle conceptuel. Plus précisément, le modèle conceptuel a proposé une relation entre la présence, les émotions et la stimulation multisensorielle. Il a également suggéré une relation entre la présence auto-rapportée et le comportement dans l'environnement virtuel. Les deux études expérimentales ont utilisé une mesure comportementale de la présence, qui se quantifie par l'amplitude avec laquelle les participants pivotent physiquement leurs épaules pour passer dans des portes virtuelles étroites (Lepecq et al., 2009 ; Mestre et al., 2016). Les deux études ont également exposé les participants à une hauteur virtuelle afin d'induire de l'anxiété.

Les résultats des deux études ont révélé que lorsque les participants se sentaient présents, ils ajustaient leur comportement en tenant compte de la largeur d'ouverture des portes virtuelles (p. ex., en pivotant leurs épaules, car l'ouverture était étroite). Cependant, les mesures auto-rapportées et comportementales de la présence n'étaient pas significativement corrélées, ce qui suggère que l'expérience subjective ne converge pas nécessairement avec le comportement en RV. D'autre part, bien que les études n'aient pas trouvé de relation significative entre la présence et l'anxiété, elles ont indiqué une relation significative entre l'anxiété et les cybermalaises.

La contribution innovante de la thèse a été de mieux comprendre la relation entre les mesures auto-rapportées et comportementales de la présence dans un contexte d'anxiété. Les résultats suggèrent qu'il est important d'utiliser diverses mesures de la présence, particulièrement lorsque l'objectif est d'évaluer le comportement des utilisateurs, car les mesures pourraient ne pas converger. De plus, dans les environnements virtuels évaluant un comportement où la conscience du corps dans l'espace est importante, le retour haptique pourrait s'avérer moins efficace en l’absence d’une représentation visuelle du corps. D’autre part, lorsque l’objectif est d’évaluer des environnements virtuels anxiogènes, il est bénéfique d’utiliser des méthodes permettant de distinguer l’anxiété des cybermalaises.

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Annexe A : Approbations obtenues pour effectuer la recherche et la rédaction de la thèse

Le 23 novembre 2020

À l'attention de :
Maxine Berthiaume
Étudiante, Université du Québec en Outaouais

Objet : Approbation éthique de votre projet de recherche

Projet #: 2021-1359
Titre du projet de recherche : Une étude sur la présence en réalité virtuelle

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Votre projet de recherche a fait l'objet d'une évaluation en matière d'éthique de la recherche avec des êtres humains par le CER de l'UQO. Suivant l'examen de la documentation reçue, nous constatons que votre projet de recherche rencontre les normes éthiques établies par l'UQO.

Un certificat d'approbation éthique qui atteste de la conformité de votre projet de recherche à la *Politique d'éthique de la recherche avec des êtres humains* de l'UQO est par conséquent émis en date du 23 novembre 2020. Nous désirons vous rappeler que pour assurer la validité de votre certificat d'éthique pendant toute la durée de votre projet, vous avez la responsabilité de produire, chaque année, un rapport de suivi continu à l'aide du formulaire *F9 - Suivi continu*. Le prochain suivi devra être fait au plus tard le :

23 novembre 2021.

Un rappel automatique vous sera envoyé par courriel quelques semaines avant l'échéance de votre certificat.

Si des modifications sont apportées à votre projet, vous devrez remplir le formulaire *F8 - Modification de projet* et obtenir l'approbation du CER avant de mettre en œuvre ces modifications. Finalement, lorsque votre projet sera terminé, vous devrez remplir le formulaire *F10 - Rapport final.*

Notez qu'en vertu de la *Politique d'éthique de la recherche avec des êtres humains*, il est de la responsabilité des chercheurs d'assurer que leurs projets de recherche conservent une approbation éthique pour toute la durée des travaux de recherche et d'informer le CER de la fin de ceux-ci.

Nous vous souhaitons bon succès dans la réalisation de votre recherche.

CERTIFICAT D'APPROBATION ÉTHIQUE

La présente atteste que le projet de recherche décrit ci-dessous a fait l'objet d'une évaluation en matière d'éthique de la recherche avec des êtres humains et qu'il satisfait aux exigences de notre politique en cette matière.

Projet # : 2021-1359

Titre du projet de recherche : Une étude sur la présence en réalité virtuelle

Chercheure principale :
Maxine Berthiaume
Étudiante, Université du Québec en Outaouais

Directeur de recherche:
Stéphane Bouchard
Professeur, Université du Québec en Outaouais

Date d'approbation du projet : 23 novembre 2020

Date d'entrée en vigueur du certificat : 23 novembre 2020

Date d'échéance du certificat : 23 novembre 2021

Caroline Tardif
Attachée d'administration, CÉR
pour André Durivage, Président du CÉR

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-03-21-6772
Titre du projet / Project Title	Une étude sur la présence en réalité virtuelle
Type de projet / Project Type	Thèse de doctorat / Doctoral thesis
Statut du projet / Project Status	Approuvé / Approved
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	19/04/2021
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	23/11/2021

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Maxine BERTHIAUME	École de psychologie / School of Psychology	Chercheur Principal / Principal Investigator
Stephane BOUCHARD	École de psychologie / School of Psychology	Superviseur / Supervisor

Conditions spéciales ou commentaires / Special conditions or comments

La date d'expiration correspond à celle du certificat d'approbation éthique du Comité d'éthique de la recherche de l'Université du Québec en Outaouais.

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Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout évènement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completedfour weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Germain ZONGO
Responsable d'éthique en recherche / Protocol Officer
Pour/For **Daniel LAGAREC** Président(e) du/ Chair of the **Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board**

Subject: Re: Inquiry regarding permission procedure for dissertation use
Date: Thursday, January 22, 2026 at 5:42:50 PM Eastern Standard Time
From: Aya Satoh
To: Maxine Berthiaume

Attention : courriel externe | external email

Dear Maxine,

Thank you for your message!

I'm happy to grant nonexclusive permission to reprint your *PRESENCE* article, "A Novel Integrated Information Processing Model of Presence" for noncommercial, scholarly use within your dissertation only.

No specific citation style is necessary, but we do ask that a full citation of the article is included along with acknowledgement of the original publication.

Please let me know if you have any questions.

With best wishes,
Aya

><><><><><><
Aya Satoh
Subsidiary Rights Associate
she/her/hers
The MIT Press
255 Main Street, 9th Floor
Cambridge, MA 02142, USA
[redacted]

From: Maxine Berthiaume
Date: Wednesday, January 14, 2026 at 8:16 PM
To: Aya Satoh
Subject: Re: Inquiry regarding permission procedure for dissertation use

Dear Aya,

Thank you again for your earlier guidance regarding permission requests.

I have decided to include the journal article in my doctoral dissertation and am writing to request permission to reproduce the full text of the article in a non-commercial, paper-based doctoral dissertation. The dissertation will be submitted to the University of Ottawa and made available in print and electronically through the university library and institutional repository.

I am the first author of the article, and the full citation is provided below for reference:
Berthiaume, M., Corno, G., Nolet, K., & Bouchard, S. (2018). A novel integrated information processing model of presence. *Presence: Teleoperators and Virtual Environments*, *27*(4), 378–399. https://doi.org/10.1162/pres_a_00336

Please let me know if you are able to grant permission for this use and whether any specific acknowledgment or citation language is required.

Thank you very much for your assistance.

Best regards,
Maxine

--
Maxine Berthiaume
Doctorante en psychologie expérimentale | PhD Candidate in Experimental Psychology
École de psychologie | School of Psychology
Université d'Ottawa | University of Ottawa
136 Jean-Jacques Lussier
Ottawa (ON), K1N 6N5, Canada

Annexe B : Scripts pour l'expérimentation

Première étude expérimentale

Script pour l'expérimentation

1- Avant la 1re immersion d'une durée de 2 minutes (environnement Pratique) :

« Cette première immersion en réalité virtuelle d'une durée d'environ 2 minutes vous permettra de vous habituer à l'équipement et d'apprendre à vous déplacer. Vous serez immergé(e) à l'extérieur d'un gratte-ciel en construction où auront lieu les prochaines immersions. Votre tâche sera de marcher en ligne droite du point de départ (MONTRER POINT DE DÉPART) jusqu'au poteau devant vous et d'appuyer sur le bouton sur le poteau. Pour marcher, marchez normalement ; vous n'avez pas besoin d'appuyer sur les boutons des manettes. Pour appuyer sur le bouton sur le poteau, vous devez simplement approcher votre main du bouton ; vous n'avez pas besoin d'appuyer sur les boutons des manettes. Lorsque vous avez appuyé sur le bouton sur le poteau, faites demi-tour et allez appuyer sur le 2e bouton. Veuillez toujours marcher en ligne droite. Pour des raisons de sécurité, marchez à une vitesse plus lente. (FAIRE UNE DÉMO) Vous pouvez à tout moment choisir librement de mettre fin à l'immersion en réalité virtuelle. Si vous avez des questions, vous pouvez me les poser pendant l'immersion.

Quand l'immersion sera terminée, je viendrai vous rejoindre pour vous aider à enlever l'équipement. »

2- Avant les immersions subséquentes d'une durée de 2 minutes chacune (environnement Principal : Contrôle, Risque de tomber et Risque de tomber + Feu) :

« Pendant cette immersion en réalité virtuelle d'une durée d'environ 2 minutes, vous serez immergé(e) à l'intérieur d'un gratte-ciel en construction. Votre tâche sera de marcher en ligne droite à partir du point de départ (MONTRER POINT DE DÉPART) et d'appuyer sur le bouton. Lorsque vous avez appuyé sur le bouton, faites demi-tour et allez appuyer sur le 2e bouton. Veuillez

marcher en ligne droite et à la même vitesse que l'immersion précédente. Vous pouvez à tout moment choisir librement de mettre fin à l'immersion en réalité virtuelle. Je ne pourrai pas répondre à vos questions ou vous parler pendant l'immersion.

Quand l'immersion sera terminée, je viendrai vous rejoindre pour vous aider à enlever l'équipement. Je vous demanderai ensuite de remplir quelques questionnaires en fonction de ce que vous avez ressenti pendant cette immersion. »

Script for Experimentation

1- Before the 1st immersion of 2 minutes (Practice environment):

"This first immersion in virtual reality of approximately 2 minutes will allow you to get used to the equipment and to learn how to move around. You will be immersed outside a skyscraper under construction in which the next immersions will take place. Your task will be to walk in a straight line from the start position (SHOW START POSITION) to the post in front of you and press the button on the post. To walk, walk normally; you do not need to press the controllers' buttons. To press the button on the post, you simply need to approach your hand toward the button; you do not need to press the controllers' buttons. Once you have pressed the button on the post, make a U-turn and go press the 2nd button. Please walk in a straight line. For safety reasons, walk at a slower speed. (DO A DEMO) You can freely choose at any time to stop the virtual reality immersion. If you have any questions during the immersion, you can ask me.

When the immersion is over, I will join you to help you remove the equipment."

2- Before the subsequent immersions of 2 minutes each (Main environment: Control, Risk of falling, and Risk of falling + Fire):

"*During this immersion in virtual reality of approximately 2 minutes, you will be immersed in a skyscraper under construction. Your task will be to walk in a straight line from the start position*

(SHOW START POSITION) and press the button. Once you have pressed the button, make a U-turn and go press the 2nd button. Please walk in a straight line and at the same speed as the previous immersion. You can freely choose at any time to stop the virtual reality immersion. I will not be able to answer your questions or talk to you during the immersion.
When the immersion is over, I will join you to help you remove the equipment. I will then ask you to fill out some questionnaires based on how you felt during this immersion."

Deuxième étude expérimentale

Script pour l'expérimentation

1- Avant la 1re immersion d'une durée de 2 minutes (environnement Pratique) :

« Cette première immersion en réalité virtuelle d'une durée d'environ 2 minutes vous permettra de vous habituer à l'équipement et d'apprendre à vous déplacer. Vous serez immergé(e) à l'extérieur d'un gratte-ciel en construction où auront lieu les prochaines immersions. Votre tâche sera de marcher en ligne droite du point de départ (MONTRER POINT DE DÉPART) jusqu'au poteau devant vous et d'appuyer sur le bouton sur le poteau. Pour marcher, marchez normalement; vous n'avez pas besoin d'appuyer sur les boutons des manettes. Pour appuyer sur le bouton sur le poteau, vous devez simplement approcher votre main du bouton; vous n'avez pas besoin d'appuyer sur les boutons des manettes. Lorsque vous avez appuyé sur le bouton sur le poteau, faites demi-tour et allez appuyer sur le 2e bouton. Veuillez toujours marcher en ligne droite. Pour des raisons de sécurité, marchez à une vitesse plus lente. (FAIRE UNE DÉMO)
Vous pouvez à tout moment choisir librement de mettre fin à l'immersion en réalité virtuelle. Si vous avez des questions, vous pouvez me les poser pendant l'immersion. Quand l'immersion sera terminée, je viendrai vous rejoindre pour vous expliquer la prochaine immersion. »

2- Avant les immersions subséquentes d'une durée de 2 minutes chacune (environnement Principal : Contrôle et Risque de tomber) :

« Pendant cette immersion en réalité virtuelle d'une durée d'environ 2 minutes, vous serez immergé(e) à l'intérieur d'un gratte-ciel en construction. Votre tâche sera de marcher en ligne droite à partir du point de départ (MONTRER POINT DE DÉPART) et d'appuyer sur le bouton. Lorsque vous avez appuyé sur le bouton, faites demi-tour et allez appuyer sur le 2^e^ bouton. Veuillez marcher en ligne droite et à la même vitesse que l'immersion précédente.

Vous pouvez à tout moment choisir librement de mettre fin à l'immersion en réalité virtuelle. Je ne pourrai pas répondre à vos questions ou vous parler pendant l'immersion. Quand l'immersion sera terminée, je viendrai vous rejoindre pour vous aider à enlever l'équipement. Je vous demanderai ensuite de remplir quelques questionnaires en fonction de ce que vous avez ressenti pendant cette immersion. »

Script for Experimentation

1- Before the 1st immersion of 2 minutes (Practice environment):

"This first immersion in virtual reality of approximately 2 minutes will allow you to get used to the equipment and to learn how to move around. You will be immersed outside a skyscraper under construction in which the next immersions will take place. Your task will be to walk in a straight line from the start position (SHOW START POSITION) to the post in front of you and press the button on the post. To walk, walk normally; you do not need to press the controllers' buttons. To press the button on the post, you simply need to approach your hand toward the button; you do not need to press the controllers' buttons. Once you have pressed the button on the post, make a U-turn and go press the 2nd button. Please walk in a straight line. For safety reasons, walk at a slower speed. (DO A DEMO)

You can freely choose at any time to stop the virtual reality immersion. If you have any questions during the immersion, you can ask me. When the immersion is over, I will join you to explain the next immersion."

2- Before the subsequent immersions of 2 minutes each (Main environment: Control and Risk of falling):

"*During this immersion in virtual reality of approximately 2 minutes, you will be immersed in a skyscraper under construction. Your task will be to walk in a straight line from the start position (SHOW START POSITION) and press the button. Once you have pressed the button, make a U-turn and go press the 2nd button. Please walk in a straight line and at the same speed as the previous immersion.*

You can freely choose at any time to stop the virtual reality immersion. I will not be able to answer your questions or talk to you during the immersion. When the immersion is over, I will join you to help you remove the equipment. I will then ask you to fill out some questionnaires based on how you felt during this immersion."

Annexe C : Questionnaires

Cyberpsychology Laboratory of UQO
Université du Québec en Outaouais
C.P. 1250, Succ. Hull, Gatineau, Québec, J8X 3X7, CANADA
Tel.: (819) 595-3900 ext. 2531; Fax: (819) 595-2250 Website: http://w3.uqo.ca/cyberpsy

PERSONAL INFORMATION

ID number: ___________ Date: ______________________

Instructions: Please answer the questions below, either by entering the answer (questions 1, 2, 8, 9 and 10) or by marking the appropriate answer with an "X" (questions 3 to 7).

1. Age: ___________
2. Sex: ___________
3. Country of birth: _____ Canada
   _____ Other
4. Dominant culture (by continent): _____ North America
   _____ South America
   _____ Europe
   _____ Africa
   _____ Asia
   _____ Australia
5. Highest level of education completed: _____ High school
   _____ CÉGEP
   _____ Bachelor's
   _____ Master's or Ph.D.
6. Socio-economic status*: _____ Low (less than $20,000)
   _____ Medium ($20,000 – 50,000)
   _____ High ($ 50,000 and above)

***Personal Income:** if you live alone and legally single.

OR

Household Income: if you live with your parents or with your partner (married or common-law).

7. Marital status: _____ Single
   _____ Common-law partner
   _____ Married
   _____ Separated/Divorced
   _____ Widowed
8. How many days per week do you play video games (PC, Wii, PlayStation, etc.)? _____
9. How many hours per week do you play video games (PC, Wii, PlayStation, etc.)? _____
10. If applicable, what types of video games do you play (e.g. first-person shooter, strategy, role playing, etc.)? _____
11. How many days per week do you play video games in VR? ______
12. How many hours per week do you play video games in VR? ______
13. If applicable, what types of video games do you play (e.g. first-person shooter, strategy, role playing, etc.)? ______

Questionnaire on Your Health

Identification Number: _______________ Date: ___________ Sex: M___ F___

Shoulder width (in cm): _______

The present study requires that participants perform an experiment in virtual reality. Before you are included in the research, we must obtain information about your health to check your susceptibility to feeling cybersickness.

Cybersickness is similar to motion sickness and can occur during or after virtual immersion. Here are some examples of symptoms:

(1) **Eye problems** (eye fatigue, blurred vision, headaches)
(2) **Disorientation** (dizziness, imbalance)
(3) **Nausea** (dizziness, burping, vomiting in rare cases)

Please answer the following questions:

DO YOU HAVE OR HAVE YOU EVER HAD ONE OF THE FOLLOWING PROBLEMS?

Psychotic or bipolar disorder …………………..…............……… □ Yes □ No
Vestibular disorders (or the inner ear) ……………….…………….… □ Yes □ No
Recurrent migraines ………………………………………………….… □ Yes □ No
Balance disorder …………………………………………………… □ Yes □ No
Important eye problems ……………………………….….…… □ Yes □ No
Cranial injury ...………………………………………….…… □ Yes □ No
Heart disease or infarction ………………………………….……. □ Yes □ No
Epileptic seizures ……………………………………………….……... □ Yes □ No
Surgery (please specify ____________________________) ……………. □ Yes □ No
Other important health problem (please specify __________________) ... □ Yes □ No
Are you pregnant (women only)? ……………………..............….. □ Yes □ No □ Not sure

DO YOU TAKE ANY MEDICATION? ………………..………..... □ Yes □ No
If so, which one(s):

Medication	Dose/frequency

Comments (if applicable):

____

____

____

____

____

In the last 24 hours, have you consumed any alcohol or drugs?
If so, which:

Alcohol/drugs	Quantity

Comments (if applicable):

____

____

____

____

____

DURING THE IMMERSION:

It is normal to feel, during a virtual immersion, some minor side effects and (e.g. discomfort, low disorientation or transient nausea, etc.). These symptoms, <u>if present</u>, are temporary and comparable to someone who watches TV closely or who suffers from motion sickness. If you experience these symptoms significantly and for more than five minutes, please notify the research assistant.

Because on rare occasions these effects may be felt after virtual reality exposure, you will be asked to wait 15 minutes after the end of the experiment before leaving the Laboratory of Cyberpsychology of UQO.

I certify the veracity of the information above. I have read and understood the contents of this form and have had the opportunity to ask my questions.

Participant's initials: ____________________________ Date: ______________________

Acrophobia Questionnaire (AQ) – Part 1: Anxiety Scale

Below we have compiled a list of situations involving height. We are interested to know how anxious (tense, uncomfortable) you would feel in each situation nowadays. Please indicate how you would feel by putting one of the following numbers (0, 1, 2, 3, 4, 5, or 6) in the space to the left of each item:

0 Not at all anxious; calm and relaxed
1
2 Slightly anxious
3
4 Moderately anxious
5
6 Extremely anxious

____ 1. Diving off the low board at a swimming pool.

____ 2. Stepping over rocks crossing a stream.

____ 3. Looking down a circular stairway form several flights up.

____ 4. Standing on a ladder leaning against a house, second story.

____ 5. Sitting in the front of a second balcony of a theater.

____ 6. Riding a Ferris wheel.

____ 7. Walking up a steep incline in country hiking.

____ 8. Airplane trip (to San Francisco).

____ 9. Standing next to an open window on the third floor.

____10. Walking on a footbridge over a highway.

____11. Driving over a large bridge (Golden Gate, George Washington).

____12. Being away from window in an office on the 15th floor of a building.

____13. Seeing window washers ten flights up on a scaffold.

____14. Walking over a sidewalk grating.

____15. Standing on the edge of a subway platform.

____16. Climbing up a fire escape to the 3rd floor landing.

____17. On the roof of a ten story apartment building.

____18. Riding an elevator to the 50th floor.

____19. Standing on a chair to get something off a shelf.

____20. Walking up the gangplank of an ocean liner.

Acrophobia Questionnaire (AQ) – Part 2: Avoidance Scale

Now that you have rated each item according to anxiety, we would like you to rate them as to avoidance. Indicate in the space to the left of the items below how much you would now avoid the situation, if it arose.

0 Would not avoid doing it
1 Would try to avoid doing it
2 Would not do it under any circumstances

____ 1. Diving off the low board at a swimming pool.

____ 2. Stepping over rocks crossing a stream.

____ 3. Looking down a circular stairway form several flights up.

____ 4. Standing on a ladder leaning against a house, second story.

____ 5. Sitting in the front of a second balcony of a theater.

____ 6. Riding a Ferris wheel.

____ 7. Walking up a steep incline in country hiking.

____ 8. Airplane trip (to San Francisco).

____ 9. Standing next to an open window on the third floor.

____10. Walking on a footbridge over a highway.

____11. Driving over a large bridge (Golden Gate, George Washington).

____12. Being away from window in an office on the 15th floor of a building.

____13. Seeing window washers ten flights up on a scaffold.

____14. Walking over a sidewalk grating.

____15. Standing on the edge of a subway platform.

____16. Climbing up a fire escape to the 3rd floor landing.

____17. On the roof of a ten story apartment building.

____18. Riding an elevator to the 50th floor.

____19. Standing on a chair to get something off a shelf.

____20. Walking up the gangplank of an ocean liner.

ID Number ____________________ Date ______________

IMMERSIVE TENDENCIES QUESTIONNAIRE
(Witmer & Singer, Version 3.01, September 1996)*
Revised by the UQO Cyberpsychology Lab (2004)

Indicate your preferred answer by marking an "X" in the appropriate box of the seven point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply. For example, if your response is once or twice, the second box from the left should be marked. If your response is many times but not extremely often, then the sixth (or second box from the right) should be marked.

1. Do you easily become deeply involved in movies or tv dramas?
|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

2. Do you ever become so involved in a television program or book that people have problems getting your attention?
|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

3. How mentally alert do you feel at the present time?
|________|________|________|________|________|________|________|
NOT ALERT MODERATELY FULLY ALERT

4. Do you ever become so involved in a movie that you are not aware of things happening around you?
|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

5. How frequently do you find yourself closely identifying with the characters in a story line?
|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

6. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?
|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

7. How physically fit do you feel today?

|________|________|________|________|________|________|________|

NOT FIT MODERATELY FIT EXTREMELY FIT

8. How good are you at blocking out external distractions when you are involved in something?

|________|________|________|________|________|________|________|

NOT VERY GOOD SOMEWHAT GOOD VERY GOOD

9. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

10. Do you ever become so involved in a daydream that you are not aware of things happening around you?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

11. Do you ever have dreams that are so real that you feel disoriented when you awake?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

12. When playing sports, do you become so involved in the game that you lose track of time?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

13. How well do you concentrate on enjoyable activities?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY WELL VERY WELL

14. How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

15. Have you ever gotten excited during a chase or fight scene on TV or in the movies?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

16. Have you ever gotten scared by something happening on a TV show or in a movie?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

17. Have you ever remained apprehensive or fearful long after watching a scary movie?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

18. Do you ever become so involved in doing something that you lose all track of time?

|________|________|________|________|________|________|________|

NEVER OCCASIONALLY OFTEN

Last version: March 2013

Original version: Witmer, B.G. & Singer. M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence*：*Teleoperators and Virtual Environments*, *7*(3), 225-240.

Questionnaire sur la Propension à l'Immersion (QPI):
Laboratoire de Cyberpsychologie de l'UQO

Validation of the French version developed by the UQO Cyberpsychology Lab:
➢ 94 French-Canadian participants completed the questionnaire;
➢ Cronbach's Alpha = .78.

Scoring:
Total: Items 1 à 18
- "Focus": Items 1 + 2 + 3 + 8 + 13
- "Involvement": Items 4 + 5 + 10 + 12 + 18
- "Emotions": Items 11 + 15 + 16 + 17
- "Games": Items 6 + 9 + 14

Norms (French version):	Mean	Standard deviation
Total	64.11	13.11
"Focus"	24.81	7.54
"Involvement"	15.33	8.67
"Emotions"	14.25	6.70
"Games"	6.56	4.95

No__________________ Date______________________

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions: Circle how much each symptom below is affecting you <u>right now</u>.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

Simulator Sickness Questionnaire***

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Validation of the French-Canadian version of the SSQ developed by the UQO Cyberpsychology Lab:

Total: items 1 to 16 (scale of 0 to 3).

- "*Nausea*": items 1 + 6 + 7 + 8 + 12 + 13 + 14 + 15 + 16.
- "*Oculo-motor*": items 2 + 3 + 4 + 5 + 9 + 10 + 11.

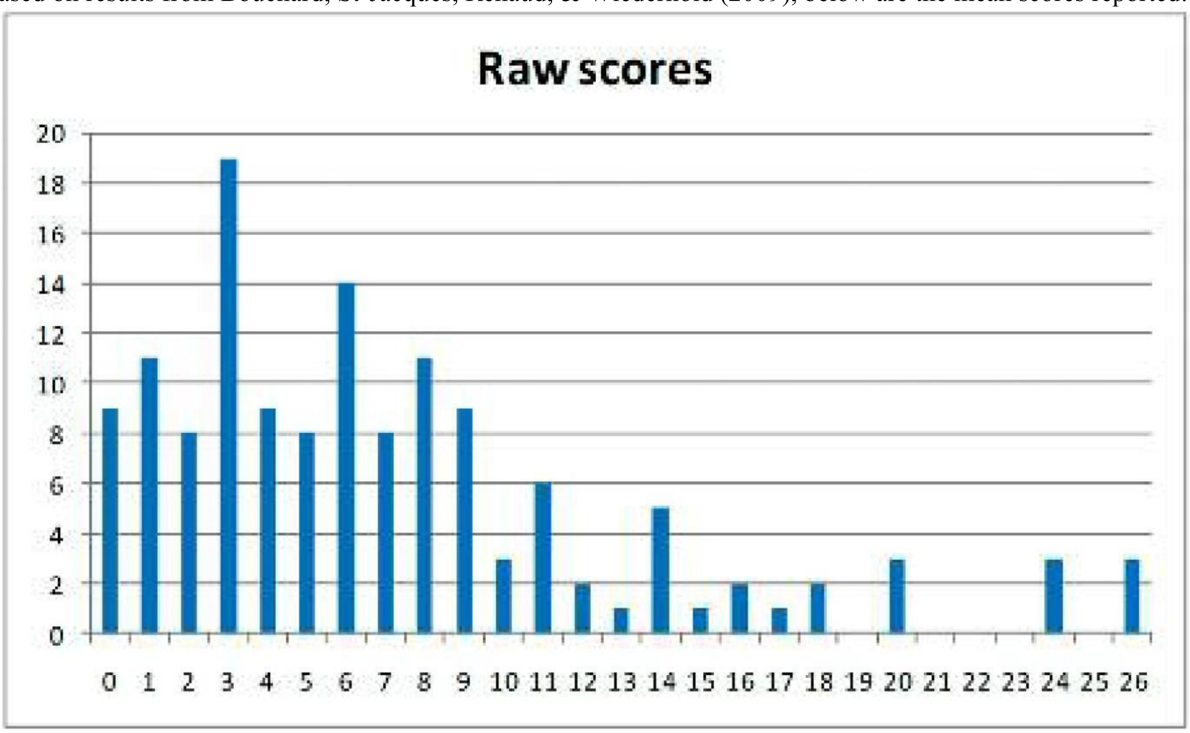
Please refer to the following articles for more information about the French-Canadian validated version:

BOUCHARD, S., Robillard, & Renaud, P. (2007). Revising the factor structure of the Simulator Sickness Questionnaire. Acte de colloque du *Annual Review of CyberTherapy and Telemedicine*, *5,* 117-122.

BOUCHARD, S., St-Jacques, J., Renaud, P., & Wiederhold, B.K. (2009). Side effects of immersions in virtual reality for people suffering from anxiety disorders. *Journal of Cybertherapy and Rehabilitation*, 2(2), 127-137.

BOUCHARD, S. Robillard, G., Renaud, P., & Bernier, F. (2011). Exploring new dimensions in the assessment of virtual reality induced side-effects. *Journal of Computer and Information Technology*, *1*(3), 20-32.

Based on results from Bouchard, St-Jacques, Renaud, & Wiederhold (2009), below are the mean scores reported:



Note. For the original scoring version, consult: Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

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SELF-EVALUATION QUESTIONNAIRE STAI Form Y-1

Please provide the following information:

ID Number______________________________________Date_____________s ___

Age_________ Gender *(Circle)* **M F** T ____

DIRECTIONS:

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you feel *right* now. that is. *at this moment.* There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	NOT AT ALL	SOMEWHAT	MODERATELY SO	VERY MUCH SO
1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I am tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel comfortable..	1	2	3	4
11. I feel self-confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I am jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady..	1	2	3	4
20. I feel pleasant	1	2	3	4

 STAIP-AD Test Form Y

Published by Mind Garden. Inc. 1690 Woodside Rd. Suite 202, Redwood City. CA 94061 www.mindgarden.com

No ID _________ Date ____________

Presence and Reality Judgement Questionnaire

Baños, Botella, Garcia-Palacios, Villa, Perpiñá, & Alcaniz (2000)
Bãnos, Quero, Salvador, & Botella (2005)

We would like to know your opinion about the experience you've just had. Please indicate with sincerity to which extent you agree with the following statements. (0 = I don't agree, 10 = I totally agree)

1. What I saw in the virtual world was similar to reality. 0 1 2 3 4 5 6 7 8 9 10
2. What I heard in the virtual world was similar to reality. 0 1 2 3 4 5 6 7 8 9 10
3. I felt bodily sensations (heat, cold, etc…). 0 1 2 3 4 5 6 7 8 9 10
4. What I experienced in the virtual world was fiction. 0 1 2 3 4 5 6 7 8 9 10
5. The experience seemed real to me. 0 1 2 3 4 5 6 7 8 9 10
6. I believe other people similar to me could have an experience similar to mine in the virtual world. 0 1 2 3 4 5 6 7 8 9 10
7. My interactions with the virtual world seemed natural to me, like the interactions in the real world. 0 1 2 3 4 5 6 7 8 9 10
8. The objects in the virtual world seemed real to me. 0 1 2 3 4 5 6 7 8 9 10
9. What I experienced in the virtual world was congruent with other experiences I had in the real world. 0 1 2 3 4 5 6 7 8 9 10
10. What I experienced in the virtual world was different from other experiences I had in the real world. 0 1 2 3 4 5 6 7 8 9 10
11. The virtual experience seemed more like a computer game, an entertainment. 0 1 2 3 4 5 6 7 8 9 10
12. The quality of the images in the virtual world influenced how real the experience seemed to me. 0 1 2 3 4 5 6 7 8 9 10
13. What I heard and the quality of the sounds in the virtual world influenced how real the experience seemed to me. 0 1 2 3 4 5 6 7 8 9 10
14. The bodily sensations I felt in the virtual world influenced how real the experience seemed to me. 0 1 2 3 4 5 6 7 8 9 10

Baños, R. M., Quero, S., Salvador, S., & Botella, C. (2005). The Role of Presence and Reality Judgement in Virtual Environments in Clinical Psychology. Cyberpsychology & Behavior, 8(4), 303-304.

Baños, R. M., Botella, C., Garcia-Palacios, A., Villa, H., Perpiñá, C., & Alcaniz, M. (2000). Presence and reality judgment in virtual environments: A unitary construct? CyberPsychology & Behavior, 3(3), 327-335.

ITC SOPI

Please read the instructions below before continuing

Instructions:

We are interested in finding out what you feel about the experience you have just had in the 'DISPLAYED ENVIRONMENT'. We use the term 'displayed environment' here, and throughout this questionnaire, to refer to the film, video, computer game or virtual world that you have just encountered. Some of the questions refer to the 'CONTENT' of the displayed environment. By this we mean the story, scenes or events, or whatever you could see, hear, or sense happening within the displayed environment. The displayed environment and its content (including representations of people, animals, or cartoons, which we call 'CHARACTERS') are different from the 'REAL WORLD': the world you live in from day-to-day. Please refer back to this page if you are unsure about the meaning of any question.

There are two parts to this questionnaire, PART A and PART B. PART A asks about your thoughts and feelings once the displayed environment was over. PART B refers to your thoughts and feelings while you were experiencing the displayed environment. Please do not spend too much time on any one question. Your first response is usually the best. For each question, choose the answer CLOSEST to your own.

Please remember that there are no right or wrong answers – we are simply interested in YOUR thoughts and feelings about the displayed environment. Please do not discuss the questionnaire with anyone who may also complete it as this may affect your answers or theirs. We should be grateful if you would also complete the 'Background Information' overleaf.

All of your responses will be treated confidentially.

Independent Television Commission

Goldsmiths UNIVERSITY OF LONDON

PART A

Please indicate HOW MUCH YOU AGREE OR DISAGREE with each of the following statements by circling just ONE of the numbers using the 5-point scale below.

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>AFTER</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

1. I felt sad that my experience was over 1 2 3 4 5

2. I felt disorientated...1 2 3 4 5

3. I had a sense that I had returned from a journey...1 2 3 4 5

4. I would have liked the experience to continue 1 2 3 4 5

5. I vividly remember some parts ofthe experience.......................................1 2 3 4 5

6. I'd recommend the experience to my friends. 1 2 3 4 5

PART B

Please indicate HOW MUCH YOU AGREE OR DISAGREE with each of the following statements by circling just ONE of the numbers using the 5-point scale below.

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

1. I felt myself being 'drawn in'.	1	2	3	4	5
2. I felt involved (in the displayed environment).	1	2	3	4	5
3. I lost track of time	1	2	3	4	5
4. I felt I could interact with the displayed environment	1	2	3	4	5
5. The displayed environment seemed natural.	1	2	3	4	5
6. It felt like the content was 'live'.	1	2	3	4	5
7. I felt that the characters and/or objects could almost touch me	1	2	3	4	5
8. I enjoyed myself.	1	2	3	4	5
9. I felt I was visiting the places in the displayed environment	1	2	3	4	5
10. I felt tired.	1	2	3	4	5

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

11. The content seemed believable to me.	1	2	3	4	5
12. I felt I wasn't *just* watching something	1	2	3	4	5
13. I had the sensation that I moved in response to parts of the displayed environment	1	2	3	4	5
14. I felt dizzy	1	2	3	4	5
15. I felt that the displayed environment was part of the real world.	1	2	3	4	5
16. My experience was intense.	1	2	3	4	5
17. I paid more attention to the displayed environment than I did to my own thoughts (e.g., personal preoccupations, daydreams etc.).	1	2	3	4	5
18. I had a sense of being in the scenes displayed	1	2	3	4	5
19. I felt that I could move objects (in the displayed environment).	1	2	3	4	5
20. The scenes depicted could really occur in the real world	1	2	3	4	5
21. I felt I had eyestrain.	1	2	3	4	5
22. I could almost smell different features of the displayed environment.	1	2	3	4	5

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

23. I had the sensation that the characters were aware of me	1	2	3	4	5
24. I had a strong sense of sounds coming from different directions within the displayed environment	1	2	3	4	5
25. I felt surrounded by the displayed environment	1	2	3	4	5
26. I felt nauseous	1	2	3	4	5
27. I had a strong sense that the characters and objects were solid	1	2	3	4	5
28. I felt I could have reached out and touched things (in the displayed environment).	1	2	3	4	5
29. I sensed that the temperature changed to match the scenes in the displayed environment.	1	2	3	4	5
30. I responded emotionally	1	2	3	4	5
31. I felt that *all* my senses were stimulated at the same time.	1	2	3	4	5
32. The content appealed to me.	1	2	3	4	5
33. I felt able to change the course of events in the displayed environment.	1	2	3	4	5

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(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

34. I felt as though I was in the same space as the characters and/or objects...1 2 3 4 5

35. I had the sensation that parts of the displayed environment
    (e.g. characters or objects) were responding to me. 1 2 3 4 5

36. It felt realistic to move things in the displayed environment......................1 2 3 4 5

37. I felt I had a headache...1 2 3 4 5

38. I felt as though I was participating in the displayed environment.............1 2 3 4 5

<u>If there is anything else you would like to add, please use the space below:</u>

<u>PLEASE CHECK THAT YOU HAVE ANSWERED ALL THE QUESTIONS</u>
<u>THANK YOU VERY MUCH FOR YOUR TIME AND PARTICIPATION</u>

ITC-SOPI

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Body Shape Questionnaire (BSQ-8B)

We should like to know how you have been feeling about your appearance over the **PAST FOUR WEEKS**. Please read each question and circle the appropriate number to the right. Please answer all the questions.

OVER THE PAST FOUR WEEKS:

	Never	Rarely	Sometimes	Often	Very often	Always
1. Have you worried about your flesh being not firm enough?..................	1	2	3	4	5	6
2. Has eating even a small amount of food made you feel fat?..................	1	2	3	4	5	6
3. Have you avoided wearing clothes which make you particularly aware of the shape of your body?...	1	2	3	4	5	6
4. Have you felt ashamed of your body?...	1	2	3	4	5	6
5. Has worry about your shape made you diet?..	1	2	3	4	5	6
6. Have you felt happiest about your shape when your stomach has been empty (e.g. in the morning)?..	1	2	3	4	5	6
7. Have you felt that it is not fair that other men are thinner than you?.	1	2	3	4	5	6
8. Have you worried about your flesh being dimply?................................	1	2	3	4	5	6

Citation: Evans, C., & Dolan, B. (1993). Body Shape Questionnaire: derivation of shortened “alternate forms”. *International Journal of Eating Disorders*, *13*(3), 315-321.

Original version: Cooper, P. J., Taylor, M. J., Cooper, Z., & Fairbum, C. G. (1987). The development and validation of the Body Shape Questionnaire. *International Journal of eating disorders*, *6*(4), 485-494.

Body Shape Questionnaire (BSQ-8B)

We should like to know how you have been feeling about your appearance over the **PAST FOUR WEEKS**. Please read each question and circle the appropriate number to the right. Please answer <u>all</u> the questions.

OVER THE PAST <u>FOUR WEEKS:</u>

	Never	Rarely	Sometimes	Often	Very often	Always
1. Have you worried about your flesh being not firm enough?	1	2	3	4	5	6
2. Has eating even a small amount of food made you feel fat?	1	2	3	4	5	6
3. Have you avoided wearing clothes which make you particularly aware of the shape of your body?	1	2	3	4	5	6
4. Have you felt ashamed of your body?	1	2	3	4	5	6
5. Has worry about your shape made you diet?	1	2	3	4	5	6
6. Have you felt happiest about your shape when your stomach has been empty (e.g. in the morning)?	1	2	3	4	5	6
7. Have you felt that it is not fair that other women are thinner than you?.	1	2	3	4	5	6
8. Have you worried about your flesh being dimply?	1	2	3	4	5	6

Citation: Evans, C., & Dolan, B. (1993). Body Shape Questionnaire: derivation of shortened “alternate forms”. *International Journal of Eating Disorders*, *13*(3), 315-321.

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