

**COGNITIVE PROCESSES UNDERLYING THE LEARNING ADVANTAGES OF
SELF-CONTROLLED FEEDBACK SCHEDULES**

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A thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
in partial fulfillment of the requirements
for the Doctorate in Philosophy degree in Human Kinetics

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**Self-controlled feedback schedules and motor learning: An information-processing
perspective**

This thesis is dedicated to

TERRY J. CARTER

My father, childhood hero, and lifelong role model.

Abstract

It is well established that an effective way to schedule knowledge of results (KR) during practice to facilitate motor learning is to allow the learner to control their KR delivery, termed self-controlled KR, rather than imposing the same schedule on the learner without choice, termed yoked KR. The learning advantages of self-controlled KR schedules have been attributed to motivational influences and/or information-processing activities with numerous researchers favouring the motivational perspective in recent years. However, many findings currently exist that are difficult to reconcile using a (purely) motivational influences explanation. For this dissertation, three experiments were conducted that aimed to better understand the learning advantages of self-controlled KR schedules from an information-processing perspective.

Chapter 2 of this dissertation provides further evidence that the learning benefits of self-controlled KR schedules depend on the option of completing the decision to receive KR after a motor response. The option of making the KR decision after a trial, rather than before a trial was suggested to allow the learner to request KR only when a comparison between estimated and actual error would maximize the informational value of the KR received. This in turn would be expected to strengthen one's error detection capabilities. This was supported by retention and transfer data where a more accurate ability to estimate one's performance in the absence of KR was found in the two self-controlled groups that were able to make a KR decision after a trial. In addition, open-ended questions regarding the strategies used for requesting KR during practice were administered at the midpoint and end of practice. An inductive thematic analysis (Chapter 3) of the self-reported KR strategies generated five themes and it was noted that strategy use changes as a function of practice. That is, the dominant strategy used during the first half of practice was different from that used during the second half of practice.

Based on the results presented in Chapters 2 and 3, Chapter 4 provides evidence that the KR-delay interval is a critical time period for reaping the learning benefits of self-controlled KR schedules. Specifically, having participants engage in an interpolated activity during the KR-delay interval eliminated the effectiveness of self-controlled KR schedules for motor learning. It is argued that the interpolated activity interfered with the processing of response-produced feedback upon movement completion that are critical for determining whether receiving KR on a given trial would provide a meaningful learning experience. Lastly, Chapter 5 provides evidence that suggests the primary motor cortex (M1) may not have a significant role in the learning advantages of self-controlled KR schedules. However, a caveat of this conclusion is that the learning benefits of practicing with a self-controlled KR schedule were negligible.

Taken together, the results presented in this dissertation suggest that informational factors associated with the processing of response-produced feedback and KR for the development of one's error-detection capabilities, rather than motivational influences are more critical for the learning advantages of self-controlled KR schedules.

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Acknowledgments

This journey towards a PhD in Human Kinetics was made richer and more intellectually stimulating by a number of people whom I'd like to acknowledge and thank.

Thanks to all my motor learning and control labmates over the years, as well as the friends I have made from other labs on the 4th floor of Montpetit. Thanks to Neil Drummond who has been my office buddy since day one. The first few weeks were relatively silent with the odd conversation here and there; however, that changed after our SCAPPS Winnipeg adventure. I would also like to thank Brad McKay; although only in the lab for a short period of time, our many conversations about research while enjoying some stouts were always thought-provoking. I would also like to thank Scott Rathwell who I have made countless memories with over the years – from the early days of bonding over conference stories and playing video games, to life as roommates (the Boys of Bronson and the Wizards of Waverley), and to achieving our goal of publishing together – you have become a close friend and respected colleague. I look forward to the adventures and memories still to come.

Thanks to many of my older friends; Scott Crozier, Scott Symonds, Russel Pearce, Jonathan Plashkes, Dan Versloot, and James Craig who have all contributed to this journey with good conversation, hanging out when I was in town or needed a break from things, and/or providing a place to stay.

I also would like to extend my thanks to the administrators (especially Anne Millette and Patricia Laliberté) of the University of Ottawa's School of Human Kinetics for their continued help over the years. I would also like to thank the University of Ottawa and the Natural Sciences and Engineering Research Council of Canada for their financial support. A doctoral Canada Graduate Scholarship supported the work presented in this thesis. Through NSERC, I was also able to receive a Michael Smith Foreign Study Supplement which allowed me to spend some time at the University of Southern California. I would like to thank Dr. Beth Fisher and Dr. Carolee Winstein for being my host supervisors at USC.

Thanks to Dr. Rose Martini and Dr. Heather Carnahan for agreeing to be the internal and external examiners, respectively, for my dissertation defense. Your comments and questions have improved the quality of this document.

Thanks to my two committee members Dr. Erin Cressman and Dr. Anthony Carlsen. Your constructive guidance and willingness to contribute your expertise over the years has shaped my development as a researcher. An extended thanks to Dr. Carlsen who I have been fortunate enough to

work closely with over the years and has been like a second supervisor. You have provided technical guidance, financial support, and have always challenged myself and others to think critically, write clearly, and ask good (and interesting) research questions. These experiences have made myself and other members of the NeuroMotor Behaviour Lab better scientists.

A big thanks to my mom and dad who have continually supported me through the many years of school. Thank you for always believing in me and providing encouragement whenever it was need. Thanks to my sisters for their support; in particular my sister Melissa for always taking an interest in the things I was working on and the occasional visit to Ottawa.

A special thanks to Vikki Smith; you have been a big part of this journey. Who would have thought all those afternoons on the patio of La Maison that first summer would result in the friendship we now have. You have definitely made me smile and laugh more than anyone else during this time and I am very grateful that we have become best friends.

A final and most deserving thanks to my supervisor Dr. Diane Ste-Marie. The wisdom, advice, expertise, and support that you have provided me (in your ever changing office locations) is something I will always appreciate and reflect positively on. You have always challenged me to think more deeply and to consider other perspectives, which has made me a more capable and curious scientist. You have always stressed the importance of developing not only as a scientist, but also as an educator and a member of the academic community; and in this endeavour, you lead by example. You always make time for your students and it is obvious that you truly care about their intellectual and personal development. I could not have asked for a better graduate supervisor, mentor, and friend. Thanks for everything Diane.

Co-Authorship Statement

I, Michael J. Carter, was primarily responsible for the research program and experimental design for all of the included experiments, with input and oversight by my thesis committee consisting of Dr. Diane M. Ste-Marie (Supervisor), Dr. Anthony N. Carlsen, and Dr. Erin K. Cressman. Data collection, data analysis, and experimental set-up including programming (Experiment 1) and program modification (Experiments 2 and 3), participant debriefing, data reduction, and statistical analysis was primarily completed by myself, Michael J. Carter. Assistance with participant recruitment and data collection was provided by Dylan Klawitter (Experiment 1), Cody Primeau (Experiment 1), Piragus Puveendran (Experiments 2 and 3), Caroline Anna Head (Experiment 2), and Victoria Smith (Experiment 3). Assistance with programming was provided by Dr. Anthony Carlsen (Experiments 1 and 2) and Ladan Maxamud (Experiment 2). Assistance with the qualitative analysis for Chapter 3 was provided by Scott Rathwell. Manuscript preparation for all chapters was completed by me, Michael J. Carter, with input and/or editorial contributions from Dr. Diane M. Ste-Marie, Dr. Anthony N. Carlsen, Scott Rathwell, Brad McKay, and Victoria Smith.

Chapters that contain content from published articles are listed below.

Chapter 2: Carter, M. J., Carlsen, A. N., & Ste-Marie, D. M. (2014). Self-controlled feedback is effective if it is based on the learner's performance: A replication and extension of Chiviakowsky and Wulf (2005). *Frontiers in Psychology*, 5, Article 1325, 1-10.

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Chapter 4: Carter, M. J., & Ste-Marie, D. M. (2016). An interpolated activity during the knowledge-of-results delay interval eliminates the learning advantages of self-controlled feedback schedules. *Psychological Research*. (EPub ahead of print Feb 18, 2016).

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1. General Introduction

From an evolutionary perspective, Wolpert (2011) emphasizes our capacity to move as more important than all other human faculties; and that sensory, memory, and cognitive processes are valuable, but only if they drive or suppress future movements. Movement is undoubtedly a critical aspect of everyday human life and the importance of understanding how our brain controls and learns movement is of considerable interest for theorists and practitioners alike. The category of human movement that will be examined herein is that of motor skills, which are operationally defined as skills that need to be learned (or relearned) and require voluntary body, head, and/or limb movement(s) to achieve a particular goal (Magill, 2011, pp. 3-4). An example of a motor skill would be learning to hit a draw shot in golf. At this point, it is important to make a distinction between movements and motor skills. Movements are behavioural characteristics of the body, the head, and/or limbs and are therefore the component parts of motor skills (Magill, 2011, p. 4). In other words, although movements must be made to perform motor skills, the characteristics of the movements made can vary considerably between individuals to achieve the same goal. Using the abovementioned golf example, Tiger Woods and Jim Furyk, both professional golfers, will regularly achieve the goal of hitting a draw shot; however, the movement characteristics of their golf swings are remarkably different. Tiger Woods has a traditional swing style that both professional and recreational golfers aim to emulate. In contrast, Jim Furyk's swing is nothing short of unorthodox and has even been described as "an octopus falling out of a tree" by golf analyst David Feherty.

As humans, we execute motor skills throughout our lifespan and these skills start to develop early in life (e.g., crawling), while new skills are acquired as we age (e.g., skating). The acquisition of novel motor skills is the focus of this dissertation and is the subdomain of motor behaviour known as motor learning. It is therefore important to operationally define and distinguish between the different

areas of motor behaviour which are motor development, motor control, and motor learning. Motor development refers to the continuous, age-related process of change in movement (i.e., maturation), as well as interacting constraints in the individual, environment, and task that drive these changes (Haywood & Getchell, 2009, p. 5). Motor control is an area of study concerned with understanding neural, physical, and behavioural aspects of human movement (Schmidt & Lee, 2011, p. 497). Multiple definitions of motor learning exist in the literature; for example, motor learning has been conceptualized as a problem-solving process in which the task goal represents a problem to be solved and the evolution of a movement configuration represents the learner's attempt to solve the problem (Adams, 1971; Gentile, 1972; Guadagnoli & Lee, 2004; Schmidt, 1975). Motor learning has also been described as a change in the capability to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice or experience (Magill, 2011; Schmidt & Lee, 2011). For the purposes of this dissertation, motor learning is operationally defined as practice-dependent changes in the capability to perform a motor skill that not only persist over an extended period of time, but are also adaptable to novel contexts or demands.

In the study of motor learning, a commonly adopted paradigm consists of having participants first perform a specific number of trials of the to-be-learned task(s), which is typically termed the practice or acquisition phase. Following the practice phase, participants return to the laboratory after a specified delay interval to perform retention and/or transfer tests. Although the length of this delay varies from experiment to experiment, a general rule of thumb is to have the delay include a period of sleep (Kantak & Winstein, 2012; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). Delayed retention and transfer tests are both measures of motor learning but each provides the researcher with different information with respect to characteristics of learning. Specifically, retention tests are used to assess the relative permanence or persistence of the memory representation that was formed as a

result of practice, whereas transfer tests assess the generalizability or adaptability of the same memory representation to novel task demands or contexts (Schmidt & Lee, 2011).

The significance of retention and/or transfer tests in motor learning experiments is exemplified by the learning-performance distinction wherein one's practice context can have profound, yet paradoxical effects on motor performance and learning (Kantak & Winstein, 2012; Schmidt & Bjork, 1992). For example, in a seminal motor learning experiment Shea and Morgan (1979) found that performance during practice was degraded when participants followed a random repetition schedule while learning multiple skills compared to a blocked repetition schedule. However, the random schedule enhanced learning as indicated by superior performance on delayed retention and/or transfer tests (see also Lee & Magill, 1983). Thus, if Shea and Morgan (1979) and Lee and Magill (1983) did not include delayed retention tests in their respective experiments, incorrect conclusions regarding the most effective way to structure practice for multiple skill learning would have been made. As such, retention and transfer tests are vital in allowing motor learning scientists to separate practice factors that may only have transient effects on performance (i.e., performance variables) from those having relatively permanent effects (i.e., learning variables).

Although practice itself is hailed as the most important factor facilitating motor learning (e.g., A. Newell & Rosenbloom, 1981), feedback is often considered the second most important factor (e.g., K. M. Newell, 1976). Feedback can be viewed as a broad term in motor learning that can be separated into intrinsic and extrinsic feedback. Intrinsic feedback (also referred to as inherent, task-intrinsic, and response-produced feedback) is information that is naturally available to the performer from sources such as, but not limited to, vision and proprioception (Sidaway, August, York, & Mitchell, 2005). Extrinsic feedback is provided to the performer from an external source such as a coach or video replay and can be used to either replace or augment intrinsic feedback (Sidaway et al., 2005). Extrinsic feedback can be further classified as knowledge of performance (KP) or knowledge of results (KR). KP is information

regarding the movement characteristics of the performer that led to a particular movement outcome, whereas KR is information regarding the accuracy of a response outcome relative to the task goal (Magill, 2011; Schmidt & Young, 1991). An example of KP would be a physical therapist informing a client to bend their knees more as they walked, whereas the scores provided to a gymnast after their beam routine by a panel of judges is an example of KR. Of these categories of extrinsic feedback, the present dissertation is concerned with KR. For the purposes of this dissertation, extrinsic feedback will herein be referred to as feedback while the terms task-intrinsic feedback and response-produced feedback will be used synonymously.

1.1. Knowledge of results (KR) and motor learning

In his influential article “Closed-loop theory of motor learning”, Adams (1971) described motor learning as a problem-solving endeavour where KR was emphasized as the most important source of information the learner needed to solve the problem (i.e., achieve the task goal). Within his theory of motor learning he ascribed functional roles to two traces: a memory trace and a perceptual trace. The purpose of the memory trace was to select and initiate the response and as such, this trace preceded the engagement of the perceptual trace. The perceptual trace provided a reference about past movement experiences and served as an online (i.e., moment to moment reference during movement) evaluation mechanism. Thus, the perceptual trace acted as a reference of correctness and its strength was directly related to experience with the task and the amount of KR the learner received. In other words, Adams (1971) predicted that KR was essential after all trials to avoid errors and facilitate motor learning. Errors were argued to weaken the perceptual trace which in turn would have a negative impact on the learning process.

A surge in research resulted from Adams’ (1971) theory of motor learning, and although empirical support was provided by some experiments, others identified shortcomings and limitations.

Consequently, a new theory of motor learning was proposed four years later by Schmidt (1975) in his seminal article “A schema theory of discrete motor skill learning”. At the outset of his article, Schmidt (1975) outlined a number of these limitations which included that Adams’ (1971) theory was only applicable to slow positioning movements, and that it was unable to account for learning without KR because of the apparent inability to develop the perceptual trace in the absence of KR. Additionally, the notion of an infinite number of stored states presented a “storage problem” for the central nervous system.

A central component of Schmidt’s (1975) theory was the concept of a generalized motor program (GMP; see Morris, Summers, Matyas, & Iansek, 1994; Summers & Anson, 2009 for reviews and discussion on the evolution of the motor program concept) which was posited to address the storage problem within Adams’ (1971) theory. The GMP was presented as an abstract memory structure capable of providing the prestructured commands for a number of motor responses within the same movement class (Schmidt, 1975, p. 232). For example, a GMP would exist for throwing that could be modified to allow a pitcher to throw a slider or a curveball rather than having the need for two separate motor programs for each type of overhand throw. Schmidt (1975) proposed that four pieces of information are stored each time a learner performs a motor response: 1) the initial conditions, 2) the response specifications, 3) the sensory consequences of the movement, and 4) the outcome of the motor response. The idea of two memory components was retained from Adams’ (1971) theory; however, Schmidt named them the recall and recognition schemas (analogous to Adams’ memory and perceptual traces, respectively). According to Schmidt (1975), the schemas were developed based on a specified relationship of the abovementioned four pieces of information. The recall schema was concerned with movement production and was developed based on the relationship between the initial conditions, the actual outcome, and the response specifications. The recognition schema was involved in performance appraisal and was composed of the relationship between the initial conditions, the actual outcome, and

the (expected) sensory consequences of the movement. Unlike Adams (1971), Schmidt (1975) did not consider errors to be detrimental to learning and instead, argued that experiencing errors would improve the error-detection/performance appraisal function of the recognition schema. As such, strengthening the schema was directly related to the learner's awareness of the actual movement outcome; thus, high levels of KR were predicted to optimize the learning process as in Adams' (1971) theory.

The impact of Closed-loop theory (Adams, 1971) and Schema theory (Schmidt, 1975) on motor learning research (see Adams, 1987, pp. 58-65 for a comprehensive review) is indisputable. As of September 2015 according to Web of Science, "Closed-loop theory of motor learning" has received a total of 722 citations (averaging 16.04 citations per year) while "Schema theory of discrete motor skill learning" has received a total of 1279 citations (averaging 31.20 citations per year). Despite these impressive numbers, both Adams and Schmidt made predictions regarding the amount of KR that was necessary to facilitate learning that did not withstand experimentation (e.g., Winstein & Schmidt, 1990; Wulf & Schmidt, 1989). It should be noted however that Adams and Schmidt were not alone in their views on the amount of KR needed to optimize learning. Research that preceded their theories had a very strict view regarding the necessity of KR such that the prevailing view at the time was that learning could not occur without it, and thus KR should be provided as frequently and as quickly as possible (Bilodeau & Bilodeau, 1958; see Bilodeau & Bilodeau, 1961 for a discussion of the prevailing view at the time; Bilodeau, Bilodeau, & Schumsky, 1959; Greenspoon & Foreman, 1956). Due to the methodological limitation of not including retention and/or transfer tests in these early examinations of KR, motor learning researchers confused the transient performance effects of KR during practice as indicative of learning. This early KR research furthers stresses the importance of the learning-performance distinction and the use of retention and/or transfer tests to make accurate conclusions about learning.

This methodological limitation in the early research on KR was highlighted by Salmoni, Schmidt, and Walter (1984) in their classic article “Knowledge of results and motor learning: A critical review and reappraisal”, which, as of September 2015, has been cited 524 times (averaging 16.38 citations per year) according to Web of Science. In this article the authors proposed the “Guidance hypothesis” which has been the impetus for KR research in motor learning since its publication. Salmoni and colleagues outlined that although KR helps to guide the learner to the correct response during practice and thus, it would seem appropriate to provide KR after 100% of trials, in actuality 100% KR schedules negatively impact learning as measured on delayed retention and transfer tests (see Magill & Anderson, 2013 for a review; c.f. Wulf & Shea, 2002). According to the Guidance hypothesis, the constant provision of KR can result in a dependence on that extrinsic source of information, which in turn causes the learner to ignore task-intrinsic feedback sources. This dependence is revealed through poor performance on retention and transfer tests under conditions in which KR is withdrawn, as is commonly done for such tests in the KR literature. There is a tremendous amount of support for the Guidance hypothesis in the motor learning literature (e.g., Bruechert, Lai, & Shea, 2003; Guadagnoli & Kohl, 2001; Maslovat, Brunke, Chua, & Franks, 2009; Schmidt, Young, Swinnen, & Shapiro, 1989; Sidaway et al., 2005; Sparrow & Summers, 1992; Weeks & Sherwood, 1994; Wulf & Schmidt, 1989; Wulf, Schmidt, & Deubel, 1993). For example, Winstein and her colleagues (Winstein, Pohl, & Lewthwaite, 1994; Winstein & Schmidt, 1990) found that faded KR schedules (50% relative frequency) enhanced learning of a targeted arm movement task compared to high frequency schedules (i.e., 100%). In summary, according to the tenets of the Guidance hypothesis an effective KR schedule is a balance between receiving KR as well as experiencing no-KR trials. The no-KR trials are thought to be important for the development of independent error-detection capabilities via task-intrinsic feedback sources; which evidently have been shown to be more effectively developed following practice with a reduced KR frequency compared to 100% KR (e.g., Bruechert et al., 2003). The main goal of KR research is to determine how its delivery can be optimized

for motor skill retention and transfer. Some examples of effective KR scheduling techniques that have been identified include summary KR (Schmidt et al., 1989), trials-delay KR (Anderson, Magill, & Sekiya, 1994), bandwidth KR (Cauraugh, Chen, & Radlo, 1993; Ugrinowitsch, Ugrinowitsch, Benda, & Tertuliano, 2010), and estimating one's error before receiving KR (Guadagnoli & Kohl, 2001; Swinnen, 1990). Another effective KR manipulation that has emerged in the last 20 years is providing learners with the opportunity to control their KR delivery (hereafter termed self-controlled KR) during the practice phase (see Sanli, Patterson, Bray, & Lee, 2013; Wulf, 2007 for respective reviews).

In a typical self-controlled KR experiment, participants in the self-controlled KR group are permitted to control their KR schedule on a trial-to-trial basis whereas participants in the control group (hereafter termed yoked) are matched to a participant in the self-controlled KR group and replicate their KR schedule, but without any choice. For example, if KR is requested on trials one, five, and nine in a block of 10 trials by a self-controlled KR participant then the yoked participant would receive KR on the same three trials; thus, the absolute number of KR trials and their relative placement throughout practice is identical for both participants. The purpose of comparing motor performance between the self-controlled and yoked groups on retention and transfer tests is to infer that having control over KR, rather than the amount of KR, is the factor contributing to any learning differences. The superiority of self-controlled KR schedules over yoked schedules have been demonstrated in children and university-aged adults (e.g., Chiviakowsky, Wulf, de Medeiros, Kaefer, & Tani, 2008; Patterson & Carter, 2010) as well as for both discrete (e.g., force production; Carter & Patterson, 2012) and serial (e.g., sequence learning; Chiviakowsky & Wulf, 2002) motor skills. Thus, the learning advantages of self-controlled KR schedules are generally considered robust. A review of the relevant self-controlled KR literature follows; however, this review is limited to experiments that used healthy younger adult participants.

1.2. Self-controlled KR and motor learning

Chiviacowsky and Wulf (2002) investigated whether learning differences would emerge between a self-controlled KR group and a yoked group that had to learn a four-digit key pressing sequence with three relative timing goals and an absolute timing goal. No performance differences between the two groups was found on a 24-hour retention test; however, the self-controlled KR group demonstrated superior response accuracy on the 24-hour transfer test. The authors also included a questionnaire in their experiment in an attempt to identify the underlying reasons why participants in a self-controlled group choose to receive and not receive KR. This multiple-choice questionnaire was completed at the end of the practice phase. The results revealed that the self-controlled KR group predominantly requested KR after perceived good trials. Interestingly, the yoked participants reported that they felt like they did not receive KR when they would have wanted to, and that they would have preferred to receive KR after the trials they thought were “good”. Chiviacowsky and Wulf (2002) suggested that an inherent motivational factor may be responsible for the learning benefits of self-controlled KR schedules and as a result, participants become more actively engaged in their learning process. However, no measures of motivation were included in the experiment.

Chen, Hendrick, and Lidor (2002) also investigated the effectiveness of a self-controlled KR schedule relative to a yoked schedule for learning a five-digit key pressing sequence. Participants practiced the task in one of four groups: self-controlled KR, experimenter-induced self-controlled KR, or one of the two corresponding yoked groups. The difference between the self-controlled KR group and the experimenter-induced self-controlled KR group was the latter received a reminder after each trial that prompted them to make their decision about receiving KR.¹ No significant differences were found between the two self-controlled KR groups on an immediate retention test; however, the experimenter-

¹ This is the traditional self-controlled KR group that has been used in the literature.

induced self-controlled KR group was significantly more accurate on the delayed two-day retention test. Importantly, both self-controlled KR groups demonstrated superior learning than their yoked counterparts. Based on the work of Chen et al. (2002) it seems that providing a decision prompt after a KR trials increases the effectiveness of a self-controlled KR schedule for long-term retention. The authors concluded that self-controlled KR schedules allowed the participants to engage in various individualized learning strategies which may have had a positive effect on information-processing that in turn may have implicitly increased intrinsic motivation. Similar to Chiviacowsky and Wulf (2002), no measure of motivation was included nor was an index of information-processing included.

Building on their earlier work (Chiviacowsky & Wulf, 2002), Chiviacowsky and Wulf (2005) enriched our understanding of self-controlled KR learning benefits by manipulating the temporal placement of the KR decision relative to executing a motor response. Specifically, one self-controlled KR group completed their KR decision before a trial (Self-Before) and the other made the same decision after a trial (Self-After). The same four-digit key pressing sequence from their 2002 experiment was used in this follow-up experiment. The results revealed that the Self-After group performed with less relative timing error on the delayed retention test; however, this difference between the groups failed to reach conventional levels of statistical significance. The authors also included a transfer test and it was found that the Self-After group performed with significantly less relative timing error than the Self-Before group. Based on these findings, Chiviacowsky and Wulf (2005) concluded that (spontaneous) error estimation processes may have a more critical role than motivation-based processes in the learning benefits of self-controlled KR schedules. However, consistent with the reviewed literature thus far, no measure of motivation was included nor was an index of error estimation capabilities. A final limitation was the lack of yoked groups within the experimental protocol.

Patterson and Carter (2010) examined whether the learning advantages of self-controlled KR schedules would extend to learning multiple motor tasks within the same practice session. In this

experiment, participants practiced three different five-digit key pressing sequences each with a different movement time goal in either a self-controlled KR group or a yoked group. It was found that the self-controlled KR group demonstrated significantly less timing error on delayed retention and transfer tests than their yoked counterparts; thus, the previously found learning benefits of self-controlled KR schedules for single task learning (e.g., Chen et al., 2002; Chiviawsky & Wulf, 2002) generalized to multiple-task learning. Patterson and Carter (2010) also administered the multiple-choice questionnaire regarding KR strategies from Chiviawsky and Wulf (2002) at the end of the practice phase. Similar to past research, a preference for KR after perceived good trials was reported by the self-controlled KR group for all three motor tasks; thus, the authors concluded that participants in the self-controlled KR group adopted a KR strategy that generalized across motor tasks. The authors also suggested that in addition to error estimation processes (e.g., Chiviawsky & Wulf, 2005), self-controlled KR participants may engage in other metacognitive strategies that subserve their decision to receive or not receive KR after a motor response. However, no metacognitive indices were included.

Further research by Hansen, Pfeiffer, and Patterson (2011) suggested that a potential limitation in the self-controlled KR research paradigm is that the typically used yoked group controls for the absolute amount of KR received, but does not accurately control for the relative scheduling of KR. That is, KR is linked to performance in the self-controlled KR group whereas it is predetermined for the yoked group and is therefore imposed on the learner in a (seemingly) random fashion. As a result, KR may be presented on trials in which the yoked participant may not have wanted KR if he or she had choice over KR. To this end, the authors introduced a novel control group and had participants learn a six-digit key pressing sequence in either a traditional self-controlled KR group (T-SC), a traditional yoked group (T-YK), or a yoked group with self-controlled KR (YK+SC). Specifically, the YK+SC group was yoked to the absolute number of KR trials of a T-SC counterpart but had control over the relative scheduling of the KR. The results revealed no differences between the groups in terms of timing error; however, the T-YK

group was significantly less accurate than the other two groups in achieving a novel timing goal on a transfer test. In terms of the number of keypress errors committed it was found that the YK+SC group committed significantly less errors than both the T-SC and T-YK in retention and transfer. Hansen et al. (2011) concluded that practicing with a restricted number of opportunities to request KR placed a greater demand on the information-processing activities of the YK+SC group as KR was a limited resource for this group relative to the T-SC group. In other words, the participants in the YK+SC group not only compared their perceived outcome to their reference of correctness, but also decided if the potential learning experience from receiving KR warranted depleting their limited number of KR requests. This additional engagement of information-processing resources was suggested to have had a positive impact on their motivation to learn the task.

Building upon the knowledge that self-controlled KR participants report a preference of requesting KR after perceived good trials (e.g., Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010), Chiviacowsky, Wulf, and Lewthwaite (2012) examined whether altering participants' perceptions of what constituted a "good" trial would differentially impact motor learning, task interest/enjoyment, perceived competence, and self-efficacy. Participants practiced an anticipation timing task in one of three groups: the Self-30 and Self-4 groups were informed that an error less than 30 ms and less than 4 ms were considered a "good" trial, respectively. The Self group did not receive any information regarding a "good" performance standard. Error scores in retention and transfer revealed no significant differences between the Self-30 and Self groups; however, both groups were significantly more accurate than the Self-4 group. At the end of practice, all participants completed the perceived competence and task interest/enjoyment subscales of the Intrinsic Motivation Inventory (IMI) as well as a self-efficacy questionnaire. Results from the IMI indicated that: 1) the Self-4 group rated their perceived competence significantly lower than both the Self-30 and Self groups and 2) the Self-30 group had significantly higher ratings of task interest/enjoyment than both the Self and Self-4 groups. It was also found that the Self-

30 and Self groups were more self-efficacious than the Self-4 group at the end of the practice phase. The authors concluded that the previously found learning advantages of self-controlled KR schedules can be lessened if learners are deprived of experiencing motivational influences such as competence through “good” performance (i.e., enhanced expectancies). However, some methodological limitations of this study included the absence of yoked groups and no baseline administration of the IMI subscales as well as the self-efficacy questionnaire.

Similar to Hansen et al. (2011), Chiviawosky (2014) addressed a limitation of the traditional yoked group used in self-controlled KR experiments. Specifically, Chiviawosky (2014) highlighted how participants in self-controlled KR groups usually ask for KR after perceived good trials and suggested that participants in traditional yoked groups were not only thwarted in terms of choice over KR (i.e., autonomy), but may have also been deprived of feelings of competency as their KR schedules are not linked to one’s performance in the same way as participants in a self-controlled KR group. To this end, Chiviawosky (2014) tested whether self-controlled KR learning benefits would persist if participants in a yoked group were provided with KR that was linked to their performance in a similar manner as their self-controlled counterparts. To achieve this, KR was always provided for two trials within a block of six trials and self-controlled participants were able to choose the two trials that KR would reflect. In the yoked group, KR was scheduled according to performance accuracy of the trials selected for KR by their self-controlled counterpart. Specifically, if a self-controlled participant requested KR for their two most accurate trials, then the yoked counterpart also received KR for their two most accurate trials within a block of six trials. An analysis of performance accuracy on KR versus no-KR trials revealed that this novel yoking technique did in fact produce the intended effect of both groups receiving KR after good trials within each block. The results revealed that despite both groups receiving KR after good trials, the self-controlled KR group was still significantly more accurate in retention. Chiviawosky (2014) also included a measure of self-efficacy that was completed immediately at the end of the practice phase and the

analysis revealed the self-controlled KR group was significantly more self-efficacious than the yoked group. Thus, having choice over one's KR was the more important factor for motor learning compared to having KR reflect good trials in an attempt to induce similar perceptions of competency between groups.

What becomes apparent from the reviewed literature is that allowing participants to control their KR schedule during practice is more effective for learning as measured using delayed retention and transfer tests compared to not having control over one's KR schedule (i.e., yoked). At this time it is also worth noting that self-controlled learning advantages are not limited to KR, but have also been demonstrated with other practice variables. Self-controlled learning advantages have been found, for example, with controlling one's KP schedule (e.g., Aiken, Fairbrother, & Post, 2012; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995; Ste-Marie, Vertes, Law, & Rymal, 2013), the use of physical assistive devices (e.g., Hartman, 2007; Wulf & Toole, 1999), the organization of practice repetitions (e.g., Keetch & Lee, 2007; Wu & Magill, 2011), the frequency of observing a skilled model demonstration (e.g., Wulf, Raupach, & Pfeiffer, 2005), the amount of practice within a fixed time period (e.g., Post, Fairbrother, Barros, & Kulpa, 2014), and controlling task difficulty during practice (e.g., Andrieux, Boutin, & Thon, 2015; Andrieux, Danna, & Thon, 2012).

Appendix A provides a table of the reviewed experiments as well as the details of some self-controlled KR experiments that were not included in literature review.

1.3. Explanations for the observed learning benefits of self-controlled KR schedules

Although the effectiveness of self-controlled KR schedules relative to yoked schedules for motor learning is well documented, the current challenge facing researchers in this area is understanding why self-controlled KR schedules enhance motor learning. To account for self-controlled KR learning advantages, two explanations are typically used by researchers: a motivation-based explanation and/or an information-processing explanation. On the one hand, proponents of the motivation-based account

suggest that when participants have control over their KR schedule, this opportunity to exercise choice satisfies the basic psychological needs of autonomy and competence, which has a positive effect on intrinsic motivation; thus, enhancing motor learning (e.g., Chiviacowsky, 2014; Chiviacowsky, Wulf, & Lewthwaite, 2012; Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015; Ste-Marie et al., 2013). On the other hand, advocates of the information-processing explanation have proposed that the learning benefits are predominately driven by the learner's ability to engage in performance-dependent KR schedules which is thought to increase the usefulness of the KR wherein participants engage in more effective and effortful information-processing activities (i.e., error estimation) than participants in a yoked group (e.g., Chiviacowsky & Wulf, 2005; Hansen et al., 2011; Patterson & Carter, 2010).

Currently, researchers have largely favoured the motivation-based explanation (e.g., Chiviacowsky, 2014; Chiviacowsky, Wulf, & Lewthwaite, 2012; Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Chiviacowsky, Wulf, Machado, & Rydberg, 2012; Lewthwaite et al., 2015; Ste-Marie et al., 2013; Wulf, Shea, & Lewthwaite, 2010). In fact, the most recent review of the self-controlled motor learning literature advocated the motivation-based explanation for future investigations (see Sanli et al., 2013). I, however, disagree with this recommendation by Sanli et al. (2013) and contend that support for a predominantly motivation-based explanation of self-controlled KR learning benefits is tenuous at best as many studies claiming to support this perspective often fail to include the requisite control groups (i.e., yoked) and/or comparison self-controlled groups. Additionally, numerous findings exist (e.g., Carter & Patterson, 2012; Chiviacowsky & Wulf, 2005; Chiviacowsky, Wulf, & Lewthwaite, 2012; Hansen et al., 2011) that are in direct disagreement with the two fundamental predictions that emanate from a purely motivational explanation: *1) Having choice or control should always result in a learning benefit compared to not having control because the former would support autonomy and competence while the latter thwarts these basic needs, and 2) Learning differences should not emerge between different self-controlled groups because all groups would still be exercising control or choice; thus, satisfying the basic*

needs of autonomy and competence for all groups. Additionally, a strong blow to the motivation-based explanation was recently reported by Ste-Marie, Carter, Law, Vertes, and Smith (2015), who used a causal modeling analysis and showed that self-efficacy (i.e., situation-specific confidence) and intrinsic motivation – cardinal psychological constructs of the motivational account – did not sufficiently explain the enhanced learning of the self-controlled group relative to their yoked counterparts. A strength of this experiment compared to past experiments was that the authors administered the self-efficacy and intrinsic motivation questionnaires at multiple time points over the three days of data collection instead of only at the end of practice. Specifically, the self-efficacy questionnaires were completed at the start of each day of data collection while the intrinsic motivation questionnaire was completed after Blocks 1 and 5 on Day One and then at the end of Days Two and Three.

1.4. Interim Summary: Self-controlled KR

The preceding sections of this Chapter have reviewed the relationship between motor learning and KR, and highlighted that self-controlled KR schedules are effective for motor skill acquisition, retention, and transfer. Moreover, the two current explanations of how self-controlled KR schedules enhance learning compared to yoked schedules were presented, and it was highlighted that some debate exists regarding which of the two is the more viable explanation. Despite this debate, it is the motivation-based explanation that seems to be considered the better explanation according to the most recent review of the self-controlled literature (Sanli et al., 2013) and the recently proposed OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016). Although I disagree with Sanli et al. (2013) and Wulf and Lewthwaite (2016), it is important to clarify that I do not discount the possibility that motivational influences resulting from a satisfaction of fundamental biological needs may have some role in why self-controlled KR schedules enhance learning. I, instead, suggest that the additional information-processing activities engaged during practice in a self-controlled group may have a greater relative contribution than any associated increases in motivation as a function of autonomy support and

feelings of competence. Support for a greater relative contribution of information-processing was recently provided by Grand et al. (2015) who examined the contributions of intrinsic motivation and enhanced KR processing (via electroencephalography) to self-controlled KR learning benefits. The results revealed that intrinsic motivation and KR processing as a set accounted for 54.8% of the variance in transfer test accuracy; however, when considering each of these predictors while accounting for the other predictor, only enhanced KR processing was a significant predictor of the superior motor learning of their self-controlled group. In sum, a purely motivational account of self-controlled learning advantages appears to be an inadequate explanation for self-controlled learning advantages and therefore, I suggest research examining more information-processing based mechanisms of self-controlled KR learning advantages is well warranted in the motor learning domain.

1.5. Non-invasive brain stimulation

Non-invasive brain stimulation is a valuable tool in research for gaining insight into brain-behaviour relationships that has potential therapeutic applications in both motor (e.g., stroke, Parkinson's disease) and cognitive (e.g., Alzheimer's disease, depression) domains (for recent reviews see Hsu, Ku, Zanto, & Gazzaley, 2015; Schulz, Gerloff, & Hummel, 2013). Two commonly used techniques for non-invasive brain stimulation are transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).

TMS is delivered to the brain by passing a strong, brief electrical current through an insulated wire coil placed on the skull. This current generates a rapidly changing magnetic field, which in turn, if the coil is held over a subject's head, induces a secondary current in the brain (Bolognini, Pascual-Leone, & Fregni, 2009). TMS can be delivered either as a single pulse, as paired pulses, or as repeated pulses (rTMS) and depending on stimulation frequency, duration, intensity, and coil shape can enhance or suppress activity in underlying cortical regions (Rossini et al., 2015; Wagner, Valero-Cabre, & Pascual-

Leone, 2007). In contrast to TMS, tDCS delivers a weak constant current (usually 0.5 to 2 mA) to brain areas underlying two scalp-mounted electrodes² (for a review see Nitsche et al., 2008): a positive anode and a negative cathode. One electrode, termed the active electrode, is placed on the scalp above the region of interest whereas the other electrode, termed the return or reference electrode, is placed elsewhere on the body (e.g., contralateral supraorbital ridge or an extracephalic area). The effects of tDCS depend on current flow, duration of application, current intensity, electrode size, and current density (quotient of current intensity and electrode size) (Nitsche et al., 2008).

Although both TMS, in its repetitive application (rTMS), and tDCS, when applied for several minutes, can be used for neuromodulation purposes, there are some methodological advantages to using tDCS over rTMS. For example, tDCS influences a larger area of the cortex than TMS and can be used to generate opposing effects through anodal and cathodal stimulation, but with similar peripheral sensations; thus, making it easier to do sham procedures compared to TMS (Filmer, Dux, & Mattingley, 2014; Nitsche et al., 2008). tDCS also acts as a neural modulator without triggering action potentials and with fewer physiological artefacts than TMS (e.g., muscle twitches and auditory noise). Furthermore, tDCS is easier to administer, is substantially cheaper, and the equipment required takes up significantly less space than that associated with TMS (Filmer et al., 2014; Nitsche et al., 2008; Nitsche & Paulus, 2011; Priori, Hallett, & Rothwell, 2009). Although both tDCS and rTMS can be easily used for offline stimulation (i.e., prior to or after a task), tDCS is much more ideal for online (i.e., during a task) stimulation because the electrodes can be easily secured to the scalp. This not only allows the subject to freely move their head during stimulation, but also means tDCS can be used with more complex motor tasks that involve the whole body (e.g., stabilometer as in Kaminski et al., 2013). For many of these reasons, tDCS is a popular choice for use in rehabilitation settings and is used in the final experiment of

² This represents the conventional 1x1 method of administering tDCS; however, tDCS can also be administered using a 4x1 method which is a form of HD-tDCS (Kuo et al., 2013).

this dissertation due to the ease at which it can be administered online. In general, anodal tDCS improves motor performance and learning (Reis & Fritsch, 2011; Reis et al., 2008) whereas the results of cathodal tDCS are mixed, with reports of decreased motor performance and/or learning or null effects (e.g., Carter, Maslovat, & Carlsen, 2015; Hayduk-Costa, Drummond, & Carlsen, 2013; Matsunaga, Nitsche, Tsuji, & Rothwell, 2004; Nitsche et al., 2008). Due to the variable nature of cathodal-tDCS, it will not be used in this dissertation.

In the motor learning literature, the majority of tDCS research has applied stimulation to the primary motor cortex (M1) (see both Hashemirad, Zoghi, Fitzgerald, & Jaberzadeh, 2016; Jacobson, Koslowsky, & Lavidor, 2012 for recent reviews and meta-analyses) and thus, stimulation protocols for M1 are well established. For example, some researchers have relied on MRI-or TMS-guided placement techniques (e.g., Hummel et al., 2005; Hummel et al., 2010; Kantak, Mummidisetty, & Stinear, 2012; Reis et al., 2009) while others have used the arbitrary positions C3 or C4 of the 10-200 EEG system for the placement of the active electrode over the M1 region of interest (e.g., Apolinario-Souza et al., 2016; DaSilva, Volz, Bikson, & Fregni, 2011; Fregni et al., 2006; Tecchio et al., 2010). Nitsche et al. (2003), for example, investigated the behavioural impact of tDCS on learning an implicit version of the serial reaction time task. Specifically, tDCS was applied to M1, the premotor cortex, or prefrontal cortex and it was found that only anodal stimulation of M1 resulted in increased skill acquisition. The authors concluded that M1 is important for the acquisition and early consolidation of an implicit motor task. Similar results for implicit motor learning have been reported by others (e.g., Cuypers et al., 2013; Kantak et al., 2012) and other researchers have found a positive effect of anodal tDCS on explicit motor learning (e.g., Karok & Witney, 2013; Stagg, Jayaram, et al., 2011). Additionally, anodal tDCS applied to M1 has also been found to enhance the retention of a visuomotor adaptation task (Galea, Vazquez, Pasricha, de Xivry, & Celnik, 2011) and the early consolidation of a previously practice skill (Tecchio et al., 2010). Collectively, these findings suggest that anodal-tDCS can be used to enhance motor learning

and therefore, it is a suitable technique to gain information about the involvement of different brain areas in processes governing motor skill learning.

1.6. Physiological effects of tDCS

It is important to note that the mechanisms of action regarding tDCS are still not entirely clear and an in-depth review of the research pertaining to this is beyond the scope of this dissertation (the interested reader is directed to Fertonani & Miniussi, 2016; Medeiros et al., 2012; Stagg & Nitsche, 2011 for detailed discussions). However, one thing that has become clear is that tDCS produces physiological effects during stimulation, as well as effects that outlast the actual stimulation period (i.e., stimulation after-effects).

During the application of tDCS, the delivered current enters the brain through the positively charged anode and flows from the anode to the negatively charged cathode (DaSilva et al., 2011). This flow of current through the cerebral cortex causes changes in the resting membrane potential of the underlying tissue (Reis & Fritsch, 2011): anodal stimulation lowers the threshold for neuronal activation (i.e., tip towards action) whereas the threshold for neuronal activation is raised through cathodal stimulation (i.e., tip towards inaction). In other words, anodal stimulation leads to increased neuronal firing while cathodal stimulation decreases neuronal firing rates. These changes in resting membrane potential are due to modulation of sodium and calcium channels found within the outer cell membrane, which is supported by pharmacological studies (e.g., Medeiros et al., 2012; Nitsche, Fricke, et al., 2003; Stagg & Nitsche, 2011). Specifically, pharmacological agents that block sodium or calcium channels respectively reduce or abolish the typically found increase in cortical excitability caused by anodal stimulation, whereas, these same drugs have no effect on cathodal-related changes in excitability (Nitsche, Fricke, et al., 2003; Stagg & Nitsche, 2011). These changes in neuronal discharge rates cause longer lasting changes in synaptic strength through processes similar to long-term potentiation and

long-term depression through modulation of NMDA receptors (Stagg & Nitsche, 2011). For example, the after-effects of stimulation can be abolished pharmacologically by blocking NMDA receptors (Filmer et al., 2014; Stagg & Nitsche, 2011). Magnetic resonance spectroscopy has shown that anodal tDCS decreases γ -aminobutyric acid (GABA) concentrations whereas cathodal tDCS inhibits glutamate (Filmer et al., 2014). Interestingly, the reduction in GABA concentration caused by anodal tDCS applied to the primary motor cortex (M1) has been shown to be highly correlated with motor learning and motor memory processes (e.g., Kim, Stephenson, Morris, & Jackson, 2014; Stagg, Bachtiar, & Johansen-Berg, 2011). tDCS has also been shown to influence activity in the cholinergic, dopaminergic, and serotonergic systems, which further suggests that the effects of tDCS are exerted through changes in synaptic plasticity (Filmer et al., 2014). In sum, both motor learning and anodal tDCS result in GABA inhibition and increased neuronal activity (Dayan & Cohen, 2011; Stagg, Bachtiar, et al., 2011); thus, it is not surprising that applying anodal-tDCS concurrently with motor training has been shown to have a positive additive effect on motor learning (e.g., Sriraman, Oishi, & Madhavan, 2014; Stagg, Bachtiar, et al., 2011). As such, tDCS will be administered online (i.e., during practice) in the final experiment of this dissertation.

1.7. Rationale for stimulation of M1 to induce changes in motor performance and learning

The primary motor cortex (M1) is a brain area that is involved in controlling the execution of voluntary movements in conjunction with other cortical and subcortical regions, such as the supplementary motor area, premotor cortex, posterior parietal cortex, cerebellum, and basal ganglia (Penhune & Steele, 2012; Ungerleider, Doyon, & Karni, 2002). In addition to its known role in movement execution, M1 has been shown to operate at a relatively high hierarchical level (Georgopoulos, 1991; Georgopoulos, Taira, & Lukashin, 1993) and is an active brain region in intricate processes like motor learning as evidenced by neuroimaging (e.g., Honda et al., 1998; Karni et al., 1995) and neurostimulation (e.g., Muellbacher, Ziemann, Boroojerdi, Cohen, & Hallett, 2001; Pascual-Leone et al., 1995) studies.

Muellbacher et al. (2001), for example, investigated changes in M1 excitability following learning of a ballistic pinching task. M1 excitability was assessed using motor evoked potentials (MEPs), which are an index of electrical activity in a muscle elicited by transcranial magnetic stimulation (TMS). The MEP data revealed that increased excitability in M1 was only found after participants had learned the ballistic pinching task. That is, there were no changes in MEPs when the corticospinal tract was directly stimulated, when participants performed the learned pinching task on a second day where no further improvements in learning occurred, and when a different, non-learned pinching task was used. The findings of Muellbacher et al. (2001) showed that M1 undergoes task-specific changes during motor learning, and is thus important to the learning process beyond its role in movement execution.

Further support for an intricate and crucial role of the M1 in motor learning has been found in experiments employing a disruptive single-pulse TMS protocol (e.g., Hadipour-Niktarash, Lee, Desmond, & Shadmehr, 2007; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Lin et al., 2009; Lin, Winstein, Fisher, & Wu, 2010). For example, when the M1 was disrupted by single-pulse TMS immediately upon movement completion during the adaptation phase, a faster rate of forgetting was found during deadaptation compared to the normal rates of forgetting found when M1 was stimulated 700 ms after the end of a movement (Hadipour-Niktarash et al., 2007). Importantly, this faster deadaptation was not due to differences in learning the visuomotor transformation as both TMS groups showed normal rates of adaptation or differences in M1 excitability. Hadipour-Niktarash et al. concluded that applying TMS immediately upon movement completion disrupted error processing in M1 and therefore, neural activity in M1 has a strong contribution to the retention of motor memories. The importance of the M1 in the retention of an acquired motor memory has also been provided by selectively disrupting M1 with rTMS after the practice phase is finished (Kantak & Winstein, 2012; Robertson, 2009; Robertson, Press, & Pascual-Leone, 2005). For example, Muellbacher et al. (2002) applied rTMS after the practice period

to M1, the dorsolateral prefrontal cortex, and the occipital cortex and found that only M1 stimulation degraded retention of the previously practiced skill.

Taken together, the findings of the reviewed experiments support the notion that M1 is not merely a by-order proxy of goal-directed movements (Lin et al., 2010), but is also involved in learning processes engaged during and after practice (i.e., encoding and consolidation: Kantak & Winstein, 2012) that result in a stronger memory representation of the acquired motor skill. Based on the importance of M1 in motor learning (Shmuelof & Krakauer, 2011), it will be targeted with tDCS in the final experiment of this dissertation.

1.8. Thesis overview, outline of experiments, and hypotheses

Our surrounding environment is filled with ample opportunities for interaction, and as humans we achieve this with our astonishing capacity to move. Thus, understanding how skilled actions are learned is an important endeavour. In this dissertation I detail three experiments that were designed to investigate the cognitive processes engaged when learners control their KR schedule during practice in order to gain a better understanding of why self-controlled KR schedules are more effective for motor learning than having the same schedule imposed on you without any choice. The experiments described herein used motor tasks that used the non-dominant upper limb in a force production task (Chapters 2 and 3) or in a waveform-matching task (Chapters 4 and 5). The non-dominant limb was used in all experiments as this introduces a level of novelty for all participants, as well as greater learning effects are found when participants learn motor skills with their non-dominant arm (e.g., Stockel & Weigelt, 2012). Importantly, the non-dominant hand was always identified using the Edinburgh Handedness Inventory (Oldfield, 1971). A change in the motor task used in Chapters 2 and 3 to that used in Chapters 4 and 5 was implemented because there were some technical issues controlling the Vernier equipment in LabVIEW. All experiments consisted of a practice phase of either 60 (Chapters 2 to 4) or 80 trials

(Chapter 5). Learning was always inferred from performance on 24-hour retention and transfer tests (Kantak & Winstein, 2012), both consisting of 10 no-KR trials.

Error measures capturing overall accuracy were used as the primary dependent variable in all experiments. Specifically, Chapters 2 and 3 used absolute error (AE), which is defined as the absolute deviation between the subject's movement and the target. AE is a very "logical" measure to use to describe a subject's overall accuracy in a task as it is sensitive to the extent that the subject was "off target" (Schmidt & Lee, 2011, p. 30). AE was also used in because much of the past self-controlled KR research has primarily used this error measure (see Sanli et al., 2013 for a review) or one that is akin to it (e.g., a points system) (Fischman, 2015). For Chapter 4, overall performance accuracy was assessed using root mean square error (RMSE), which is the dependent measure typically used for the waveform matching task (e.g., Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010, 2011; Kovacs, Boyle, Grutmatcher, & Shea, 2010; Lin et al., 2008; Lin et al., 2010). RMSE is sensitive to spatial and temporal errors (Kovacs et al., 2010) and is the mean difference between the target waveform and the participant's trajectory calculated over the participant's actual movement time (Lin et al., 2010). RMSE was calculated after synchronizing the onset of the target waveform with the participant's response. Although the same waveform task was used in Chapter 5, RMSE was not used as dependent measure. The reason for this was based on past research showing that it is the overall temporal component (i.e., movement time goal) of the waveform that is amenable to neurostimulation (Lin et al., 2009). Similar to the procedures of Lin et al. (2009), temporal accuracy was quantified using absolute constant error of the movement time with respect to the goal time ($|CE|_{MT}$) and spatial accuracy was quantified using the sum of $|CE|$ in movement amplitude for each reversal point in the movement trajectory ($\sum |CE|_{AMP}$). $|CE|$ is a transformation of constant error (CE), wherein the sign is taken away after the average CE for a series of trials has been calculated; thus, $|CE|$ differs from AE in that for AE the sign is taken away

immediately after calculating the difference between a single score and the target (Schmidt & Lee, 2011, pp. 30-31).

As stated previously, the overall goal of this dissertation was to gain a better understanding of the information-processing activities underlying self-controlled KR learning advantages. The main objectives (bolded) and hypotheses (italicized) for Chapters 2 to 5 are outlined briefly below.

1. In Chapter 2, I describe the experiment in which I investigated whether **a positive additive effect of motivational and informational factors is responsible for self-controlled KR learning benefits**. To this end, a replication and extension of Chiviakowsky and Wulf's (2005) experiment that investigated the temporal placement of the KR decision (either before or after a motor response) on the learning benefits of self-controlled KR schedules was conducted. This experiment introduced a novel self-controlled KR group that completed the KR decision both before and after a motor response. Corresponding yoked groups for all self-controlled groups (Self-Before, Self-After, Self-Both) were included and an index of error estimation was incorporated in the design, thereby addressing the identified limitations in the original experiment. The main hypothesis of this experiment was that *if the learning benefits of self-controlled KR schedules are attributable to a positive additive effect of motivational and informational factors, then the Self-Both group would show superior learning compared to the Self-Before and Self-After groups*.
2. In Chapter 3, I report on an exploratory component regarding strategy data that was collected during the experiment reported in Chapter 2. Specifically, participants in all self-controlled groups were queried on their strategies for requesting KR during practice using an open-ended question approach at two different time points (midpoint and end of practice). Thus, the objective of Chapter 3 was **to describe strategy adoption via inductive thematic analysis and**

explore whether strategy use influences motor skill retention. Inductive thematic analysis is a bottom-up data driven process that involves coding participants' responses without trying to fit them into pre-existing theoretical notions (Braun & Clarke, 2006). *Based on the extant self-controlled KR literature, we hypothesized that participants were likely to report requesting KR after trials that were perceived as "good" (e.g., Patterson & Carter, 2010) and that a shift in the dominant strategy used between the two halves of practice would emerge (e.g., Carter & Patterson, 2012).*

3. In Chapter 4, I describe the experiment that investigated **whether the KR-delay interval was a critical period for information-processing activities underlying the self-controlled KR learning advantages.** The KR-delay interval is the period of time between the completion of a motor response and the presentation of KR for that trial (Magill, 2011). In self-controlled KR research, the KR-delay interval culminates in the KR decision. During practice, participants either experienced an "empty" KR-delay interval or were required to perform an interpolated activity. From an information-processing viewpoint, the interpolated activity can be thought of as a secondary task which is used to interfere with the normal processing activities engaged during the KR-delay interval. The interpolated activity used was a modified version of the number-solving task used by Marteniuk (1986) that required participants to guess the identity of a two-digit number through trial and error. Two self-controlled KR groups were created: one that experienced an empty KR-delay interval (Self-Controlled+Empty) and one that performed the interpolated activity during the KR-delay interval (Self-Controlled+Interpolated). Corresponding yoked groups were included for both self-controlled groups (Yoked+Empty and Yoked+Interpolated). *It was hypothesized that if the information-processing activities occurring in the KR-delay interval are not critical for self-controlled KR learning benefits, then no learning*

differences should be found between the two self-controlled groups, but both should demonstrate superior learning compared to their yoked counterparts.

4. Chapter 5 consists of the experiment in which I investigated **whether the learning benefits of self-controlled KR schedules could be enhanced using tDCS**. Specifically, anodal or sham tDCS was applied to the contralateral M1 of the performing hand of participants in self-controlled or yoked groups. This resulted in four groups: Self-Anodal, Self-Sham, Yoked-Anodal, and Yoked-Sham. *It was hypothesized that the Self-Anodal group would demonstrate superior learning compared to the Self-Sham group and that independent of tDCS, both self-controlled groups would show enhanced learning compared to their respective yoked groups.*

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2. Chapter 2

Self-controlled feedback is effective if it is based on the learner's performance: A replication and extension of Chiviawowsky and Wulf (2005)¹

¹ A version of this chapter has been published:

Carter, M. J., Carlsen, A. N., & Ste-Marie, D. M. (2014). Self-controlled feedback is effective if it is based on the learner's performance: A replication and extension of Chiviawowsky and Wulf (2005). *Frontiers in Psychology*, 5, Article 1325, 1-10.

2.1. Abstract

The learning advantages of self-controlled feedback schedules compared to yoked schedules have been attributed to motivational influences and/or information-processing activities with many researchers adopting the motivational perspective in recent years. Chiviawsky and Wulf (2005) found that feedback decisions made before (Self-Before) or after a trial (Self-After) resulted in similar retention performance, but superior transfer performance resulted when the decision to receive feedback occurred after a trial. They suggested that the superior skill transfer of the Self-After group likely emerged from information-processing activities such as error estimation. However, the lack of yoked groups and a measure of error estimation in their experimental design prevents conclusions being made regarding the underlying mechanisms of why self-controlled feedback schedules optimize learning. Here, we revisited Chiviawsky and Wulf's (2005) design to investigate the learning benefits of self-controlled feedback schedules. We replicated their Self-Before and Self-After groups, but added a Self-Both group that was able to request feedback before a trial, but could then change or stay with their original choice after the trial. Importantly, yoked groups were included for the three self-controlled groups to address the previously stated methodological limitation and error estimations were included to examine whether self-controlling feedback facilitates a more accurate error detection and correction mechanism. The Self-After and Self-Both groups demonstrated similar accuracy in physical performance and error estimation scores in retention and transfer, and both groups were significantly more accurate than the Self-Before group and their respective Yoked groups ($p's < .05$). Further, the Self-Before group was not significantly different from their yoked counterparts ($p's > .05$). We suggest these findings further indicate that informational factors associated with the processing of feedback for the development of one's error detection and correction mechanism, rather than motivational processes are more critical for why self-controlled feedback schedules optimize motor learning.

2.2. Introduction

A robust learning advantage for motor skill retention and transfer has consistently been demonstrated when learners are permitted control over their feedback schedule on a trial-to-trial basis (hereafter termed self-controlled) relative to externally-imposed feedback schedules (hereafter termed yoked) (see Sanli, Patterson, Bray, & Lee, 2013; Wulf, 2007 for reviews). In this context, feedback refers to information that may not normally be available to the learner (i.e., knowledge of results [KR]), but can be provided by an external source such as a coach to augment naturally occurring movement-related feedback. The purpose of comparing motor performance on retention and transfer tests between groups with, and without control over their KR schedule is to confirm that any group differences in learning are attributable to having control over KR during practice, rather than a function of the frequency to which KR was provided or the amount of practice itself. Moreover, retention and transfer tests provide complimentary, yet different information regarding the characteristics of learning. Retention tests evaluate the relative permanence of one's performance capability acquired during practice while transfer tests assess the generalizability or adaptability of what was learned in practice (Kantak & Winstein, 2012; Schmidt & Lee, 2011, p. 462).

Although the learning benefits of self-controlled KR schedules are well documented (see Sanli et al., 2013; Wulf, 2007 for reviews), no clear explanation of the mechanisms underlying the optimization of motor learning under these conditions exists. Currently, two explanations are predominantly used to account for the learning benefits of self-controlled KR schedules in the motor domain. According to the motivational (or psychological) explanation, a self-controlled KR schedule satisfies the basic psychological needs of autonomy and competence, as KR can be chosen for perceived successful trials, which results in higher levels of intrinsic motivation and subsequent learning (e.g., Chiviacowsky, 2014; Chiviacowsky, Wulf, & Lewthwaite, 2012; Ste-Marie, Vertes, Law, & Rymal, 2013). Recently, many

researchers investigating the underlying mechanisms for the learning advantages of self-controlled KR have largely favoured this motivational perspective (e.g., Chiviacowsky, 2014; Chiviacowsky, Wulf, & Lewthwaite, 2012; Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Chiviacowsky, Wulf, Machado, & Rydberg, 2012; Ste-Marie et al., 2013; Wulf, Shea, & Lewthwaite, 2010). In fact, Sanli et al. (2013) encouraged future investigations to enhance our understanding of self-controlled learning benefits from the motivational perspective via Self-determination theory (Ryan & Deci, 2000).

The alternative to the motivational view is the information processing perspective which suggests that the learning benefits of self-controlled KR are predominately driven by the learner's ability to engage in performance-dependent KR strategies – which increases the relative value of the feedback received compared to yoked schedules which are not performance-dependent (e.g., Hansen, Pfeiffer, & Patterson, 2011; Patterson & Carter, 2010; Patterson, Carter, & Sanli, 2011). For example, some researchers have found that participants in self-controlled groups report a preference for requesting KR after perceived good trials (Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010) while others have reported mixed results for the self-reported strategies used during practice (see both Patterson et al., 2011; Patterson, Carter, & Hansen, 2013). More recently it has been shown that participants in a self-controlled KR group reported a strategy of requesting KR equally following perceived good and poor trials early in practice, but switched to requesting KR only after perceived good trials during the later stages of practice (Carter & Patterson, 2012). Together these findings highlight the performance-dependent nature of self-controlled KR schedules throughout the practice phase.

Although the motivational perspective has garnered much attention in recent years (see Sanli et al., 2013; Wulf et al., 2010 for discussions), there is a seemingly overlooked finding from a paper by Chiviacowsky and Wulf (2005). In that paper, the authors stated that informational processes associated with the processing of KR, rather than motivational processes, may be more critical for explaining why self-controlled KR schedules optimize motor learning. To elaborate, Chiviacowsky and Wulf investigated

whether the temporal locus of the KR decision, made either before (Self-Before) or after (Self-After) motor execution, differentially impacted learning of a sequential timing task. It was argued that if the learning benefits of self-controlled KR were predominately related to motivational influences, then the timing of one's KR decision should not affect motor learning as both groups would still be self-controlling their KR delivery. In contrast, if information-based factors related to the processing of KR (e.g., subjective performance evaluations) have a greater contribution to the learning benefits, then motor learning should depend on the timing of the KR decision (Chiviakowsky & Wulf, 2005). The authors found no significant group differences on a delayed retention test; however, the Self-After group was significantly more accurate than the Self-Before group on a delayed transfer test². To account for these findings, error scores on KR versus no-KR trials during practice were examined and it was found that errors were significantly lower on KR trials compared to no-KR trials for both groups. This finding for the Self-After group replicated their earlier work (see Chiviakowsky & Wulf, 2002) but was an unexpected finding for the Self-Before group. As a result, Chiviakowsky and Wulf (2005) suggested participants in the Self-Before group may have "tried harder after deciding they wanted feedback for a particular trial" (p. 46) so they would have a success experience once KR was provided. The authors further speculated that both groups "may have benefited from a motivational influence of self-control...[but] this factor alone cannot explain the learning advantages [on the transfer test] of the Self-After condition" (p. 46). It was therefore concluded that being able to make the KR decision after movement execution allowed learners to base their decision on their (estimated) performance (Chiviakowsky & Wulf, 2005); thus, resulting in informational benefits. Further, they argued that a more accurate error detection and correction mechanism may at least partially subserve the learning benefits

² The authors argued that transfer performance is a more sensitive measure of learning than retention performance. However, both retention and transfer performance should be viewed as important indices of learning as they provide different, yet complimentary information regarding characteristics of learning (i.e., permanence and adaptability of a memory representation for skill, respectively).

of self-controlled KR schedules. The methodological limitation of no yoked groups in their experiment however, does not allow for conclusions regarding the underlying mechanisms, whether motivational or informational, for why self-controlled KR learning advantages emerge. Their experimental design also did not include any measure associated with error detection and correction, and thus further research including an assessment of this mechanism as a critical factor for why self-controlled KR schedules optimize motor learning is warranted (see Carter & Patterson, 2012).

In the present experiment, we revisited the work of Chiviacowsky and Wulf (2005) and addressed their primary methodological limitation via the addition of yoked groups in order to investigate the involvement of motivational and informational processes to the learning advantages of self-controlled KR schedules. Our experiment also extends their work through two features: First, all participants were asked to make performance estimations after each trial during the retention and transfer tests of the experiment to examine the hypothesis that error estimation processes have an important role in self-controlled KR learning benefits (Carter & Patterson, 2012; Chiviacowsky & Wulf, 2005). Second, we included a novel self-controlled group that was provided the option to request KR before a trial but could then change or stay with their original decision after a trial. Thus, three self-controlled KR groups were compared: one that completed their KR decision before a trial (hereafter Self-Before), one that made the decision after a trial (hereafter Self-After), and one in which learners decided both before and after a trial (hereafter Self-Both). The Self-Both group was added to test a potential positive additive effect of motivational and informational factors related to self-controlling one's KR delivery. More specifically, and in line with ideas presented by Chiviacowsky and Wulf (2005), this group may be motivated to try harder to have a "success experience" after choosing KR for an upcoming trial; however, they could then also engage in subjective performance evaluations to determine whether KR would in fact be valuable for that particular trial. Thus, these learners would have the assumed advantages associated with both motivational and informational processes for both motor skill retention

and transfer, and may therefore benefit more than those learners who only gain a single assumed advantage (i.e., the Self-Before group [primarily motivational] and the Self-After group [primarily informational]).

Of secondary interest was to examine whether participants in the self-controlled groups would exhibit decreased error on trials where KR was requested (e.g., Chiviacowsky & Wulf, 2002, 2005) as a strategy to have “success experiences” to protect perceptions of competence (Chiviacowsky, 2014; Chiviacowsky, Wulf, & Lewthwaite, 2012). It was predicted that if motor learning is optimized through self-controlled KR schedules due to a combination of motivational influences and information processing activities, then the Self-Both group should demonstrate superior learning relative to the Self-Before and Self-After groups. Moreover, differences in skill transfer were expected between the Self-Before and the Self-After group (e.g., Chiviacowsky & Wulf, 2005). Consistent with the existing literature, all self-controlled feedback groups were expected to demonstrate enhanced motor learning and a more accurate error detection and correction mechanism relative to their respective yoked counterparts.

2.3. Materials and method

2.3.1. Participants

Forty-eight volunteers (30F, 18M; Mage = 21.35, SD = 1.12 years) with no self-reported sensory or motor dysfunctions participated in the experiment after giving written informed consent. The first 24 participants were randomly assigned to one of the self-controlled groups while the last 24 participants were randomly assigned to one of the yoked groups. This resulted in six equal-sized ($n = 8$) groups: Self-Before, Self-After, Self-Both, Yoked-Before, Yoked-After, and Yoked-Both. The experiment was approved and conducted in accordance with the ethical guidelines set by the Health Sciences and Science Research Ethics Board at the University of Ottawa.

2.3.2. Task and apparatus

Participants were informed the goal of the motor task was to propel a low-friction slider along a horizontal rail such that it would stop at a target distance of 133 cm (see Figure 2.1). Thus, the task was similar to a force production task in which the participant is required to learn the correct amount of force to exert to reach the goal distance. Participants were in a seated position and grasped the handle of the slider (12.1 cm x 17.1 cm [L x H]; 455 g) with a transverse palmar grip using their non-dominant hand. Hand dominance was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The horizontal rail was 261.6 cm in length with the first 50 cm of the rail defined as a pre-response area. A wooden barrier (78.7 cm x 45.7 cm) was located 50 cm from the start of the horizontal rail and participants were informed the wooden barrier represented the 0 cm position relative to the target distance. The barrier contained an opening slightly larger than the slider to allow unobstructed travel along the rail. Moreover, all participants wore opaque goggles during all experimental phases to ensure they did not look through the small opening to see the end location of the slider. This was to ensure participants would rely on proprioceptive information to learn the task rather than visual information. A Vernier Motion Detector 2 (ultrasound frequency of 50 kHz with an accuracy of ± 2 mm within a range of 0.5 to 6 m) was mounted to the end of the horizontal rail and was used to detect the end position of the slider relative to the zero position (i.e., wooden barrier) during all experimental phases. The Vernier Motion Detector 2 was connected to a Vernier LabPro[®] that collected and transmitted the position data of the slider on each trial, and was calibrated each day prior to testing. The Vernier Motion Detector 2 and the Vernier LabPro[®] were controlled using a customized LabVIEW program (National Instruments Inc.) which also controlled the timing of all experimental stimuli and stored all data for offline analysis.

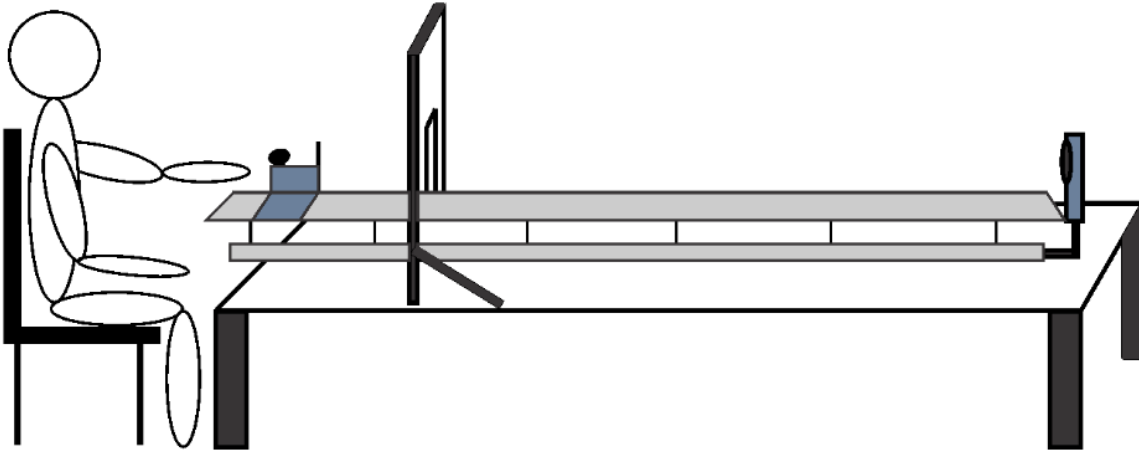


Figure 2.1. A schematic representation of the slider apparatus.

2.3.3. Experimental design and procedure

The self-controlled groups were informed they would have control over their KR schedule, but with the restriction they must request KR on three of 10 trials in each practice block (consistent with Chiviawsky & Wulf, 2005). KR requests were restricted to ensure that any potential learning differences between the three self-controlled groups could not be due to differences in the relative frequency of KR during practice. The self-controlled groups were also instructed to only request KR when necessary because they would eventually be required to perform the task without KR. Participants in the self-controlled groups were further informed about when they would be asked to make their KR decision in accordance with their respective experimental group (i.e., informed they would be asked before, after, or both before and after a trial). Participants in the yoked groups received the identical KR schedule to that of a self-controlled counterpart in each practice block. Participants in the yoked groups were informed that KR would be provided according to a pre-determined schedule and that the researcher would indicate whether KR would or would not be provided either before, after, or both before and after a trial.

Consistent with the methods of Chiviawsky and Wulf (2005), testing was completed over two consecutive days, with the practice phase on Day 1 and the retention and transfer tests on Day 2. The practice phase began with participants reading through a series of instructions outlining the goal of the motor task and their respective experimental group. During the practice phase, all participants completed 60 trials (6 blocks of 10 trials) with a relative KR frequency of 30% (i.e., 3 KR trials per 10 trial block). For all experimental trials, participants were allowed up to 5 s to complete their motor action. On KR trials during practice, participants removed their opaque goggles to view KR that was displayed on a 19-inch LCD monitor for 3 s. The KR display consisted of the target distance (133 cm), the distance of their motor response (e.g., 123), and their constant error score (e.g., -10 cm). The timeline of a typical experimental trial is illustrated in Figure 2.2. The retention and the transfer tests consisted of 10 no-KR

trials with the transfer test requiring participants to adapt to a new target distance (165 cm). To further test the notion that an enhanced ability to detect and correct errors may underlie the learning benefits of self-controlled KR schedules, all participants were asked to estimate their perceived outcome of each motor response during retention and transfer.

2.3.4. Statistical analyses

Absolute error (AE) scores were calculated for all phases of the experiment. To examine the development of the error detection and correction mechanism, the absolute difference (AD) between the participant's estimated outcome and their actual outcome was calculated for the retention and transfer tests. These dependent measures were used to index changes in motor performance and learning and were analyzed using analysis of variance (ANOVA) procedures described below. An alpha level of $\leq .05$ was considered significant and where appropriate, partial eta squared (η_p^2) is reported to provide an estimate of effect size. To decompose significant effects, post hoc tests were administered using Tukey's HSD for practice data and Holm-Bonferonni procedures for retention and transfer data. In cases where sphericity was violated, Greenhouse-Geisser adjusted p values are reported.

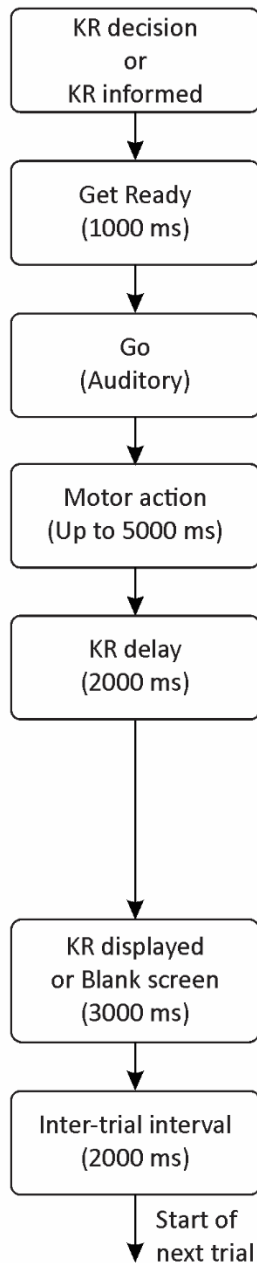
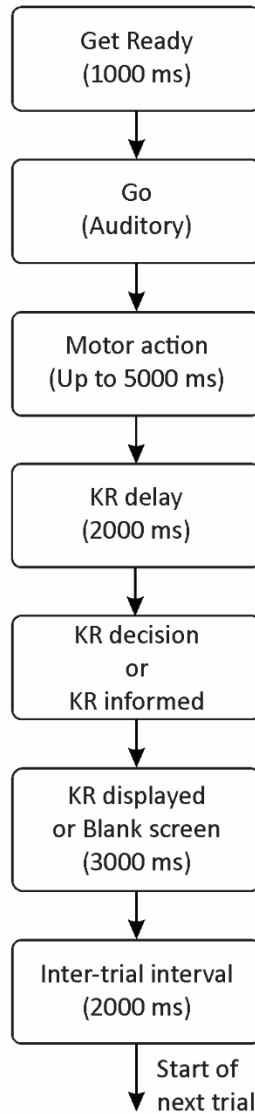
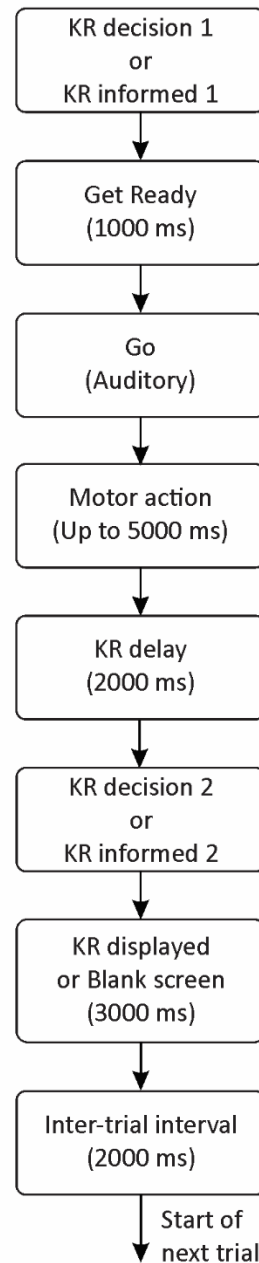
Self-Before and Yoked-BeforeSelf-After and Yoked-AfterSelf-Both and Yoked-Both

Figure 2.2. Temporal events in a typical practice trial as a function of experimental group.

2.4. Results

2.4.1. Practice

2.4.1.1. Absolute error

AE scores (cm) for practice are shown in Figure 2.3 (B1 to B6) and were analyzed using a 2 (Choice: Self, Yoked) x 3 (Decision: Before, After, Both) x 6 (Block) mixed-model ANOVA with repeated measures on Block. All groups showed a reduction in AE across practice blocks, which was supported by a significant main effect, $F(5, 210) = 39.20$, $p < .001$, $\eta_p^2 = .48$. A significant main effect of Decision was also found, $F(2, 42) = 4.50$, $p = .017$, $\eta_p^2 = .18$, with Tukey's post hoc analyses showing that independent of choice only the After groups were significantly more accurate during practice than the Before groups. All other comparisons failed to reach statistical significance (p values $> .05$).

2.4.1.2. AE on KR versus no-KR trials

Consistent with the analysis used by Chiviacowsky and Wulf (2005), mean AE was calculated on KR and no-KR trials for the first and second half of the practice phase (see Table 2.1) and analyzed using a 2 (Choice) x 3 (Decision) x 2 (Type: KR, no-KR) x 2 (Half: First, Second) mixed-model ANOVA. A significant Choice x Type interaction was found, $F(1, 42) = 5.80$, $p = .021$, $\eta_p^2 = .12$, and Tukey's post-hoc testing showed the Yoked groups performed with lower AE on no-KR relative to KR trials, whereas no differences were noted on KR versus no-KR trials for the Self-controlled groups. There was also a significant Half x Type interaction, $F(1, 42) = 14.96$, $p < .001$, $\eta_p^2 = .26$, with Tukey's post-hoc tests revealing that AE on KR trials for the first half of practice was significantly greater than AE on KR trials for the second half of practice and no-KR trials for both halves of practice. Moreover, AE on no-KR trials was significantly lower in the second half relative to the first half of practice.

Table 2.1

Mean AE ($\pm$ SE) scores (cm) on KR trials and no-KR trials during the first and second half of practice for each experimental group

	First half (trials 1-30)		Second half (trials 31-60)	
Group	KR	no-KR	KR	no-KR
Self-Before	42.41 (3.64)	<u>36.92 (2.72)</u>	26.37 (3.72)	<u>26.05 (2.20)</u>
Self-After	<u>31.22 (2.98)</u>	32.21 (3.68)	<u>20.50 (2.89)</u>	24.96 (2.77)
Self-Both	36.82 (2.69)	<u>30.62 (2.29)</u>	<u>20.26 (1.07)</u>	26.83 (3.00)
Yoked-Before	44.39 (5.72)	<u>35.36 (2.57)</u>	<u>28.57 (4.14)</u>	30.20 (3.80)
Yoked-After	31.94 (2.81)	<u>27.44 (1.85)</u>	<u>19.34 (2.74)</u>	22.01 (1.23)
Yoked-Both	40.52 (3.66)	<u>34.82 (2.65)</u>	31.85 (3.09)	<u>25.73 (1.65)</u>

Note. For each practice half, the boldfaced and underlined numbers highlight the trial type (either KR or no-KR) for which performance was more accurate during practice.

2.4.1.3. KR scheduling within practice blocks

Although the relative frequency of KR was controlled (i.e., 3 KR trials per block) it was possible that participants could distribute their KR trials differently within the 10 trials which in turn could produce differential effects on performance and learning. To rule this out, we determined the frequency distribution for which trials (1 to 10) the three self-controlled groups self-scheduled their KR collapsed across practice (see Table 2.2). Both the Self-Before and the Self-Both groups used their KR requests predominantly on trials 1, 2, and 3 whereas the Self-After group predominantly requested KR on trials 1, 3, and 4. Thus, all three self-controlled groups appear to have favoured more of a massed schedule when using their KR requests wherein KR was requested primarily for early trials rather than later trials in a practice block.

Table 2.2

The amount KR was requested for trials 1 to 10 collapsed across practice for the three self-controlled groups (and its percentage of total KR request opportunities in parentheses).

Trial number										
Group	1	2	3	4	5	6	7	8	9	10
Self-Before	<u>26 (18.1%)</u>	<u>22 (15.3%)</u>	<u>20 (13.9%)</u>	19 (13.2%)	13 (9%)	8 (5.6%)	12 (8.3%)	13 (9%)	6 (4.2%)	5 (3.5%)
Self-After	<u>32 (22.2%)</u>	16 (11.1%)	<u>24 (16.7%)</u>	<u>21 (14.6%)</u>	17 (11.8%)	17 (11.8%)	9 (6.3%)	4 (2.8%)	3 (2.1%)	1 (0.7%)
Self-Both	<u>34 (23.6%)</u>	<u>26 (18.1%)</u>	<u>25 (17.4%)</u>	10 (6.9%)	6 (4.2%)	15 (10.4%)	6 (4.2%)	8 (5.6%)	8 (5.6%)	6 (4.2%)

Note. The boldfaced and underlined numbers highlight the three trial numbers within a block for which KR was most often requested.

2.4.2. Retention and transfer

2.4.2.1. Absolute error

AE scores for the retention and transfer tests are shown in Figure 2.3 (B7, B8 respectively) and were analyzed using separate 2 (Choice) x 3 (Decision) two-way ANOVAs. In retention, the main effects for Choice and Decision were superseded by a significant Choice x Decision interaction, $F(2, 42) = 7.13$, $p = .002$, $\eta_p^2 = .25$. Holm-Bonferonni post-hoc comparisons revealed that although the Self-After ($M = 10.04$, $SE = 1.89$) and Self-Both ($M = 12.45$, $SE = 3.58$) groups did not differ significantly, they were both significantly more accurate in retention than the Self-Before group ($M = 29.18$, $SE = 4.08$). In addition, Self versus respective Yoked comparisons revealed: (1) both the Self-After and Self-Both groups had significantly less AE than their Yoked counterparts (Yoked-After: $M = 24.87$, $SE = 3.04$; Yoked-Both: $M = 35.66$, $SE = 3.55$); and (2) the Self-Before and the Yoked-Before ($M = 27.35$, $SE = 3.66$) groups did not differ significantly.

Similar to retention, the main effects for Choice and Decision during the transfer test were superseded by a significant Choice x Decision interaction, $F(2, 42) = 3.46$, $p = .041$, $\eta_p^2 = .14$. Holm-Bonferonni post-hoc analyses revealed the following: (1) the Self-After ($M = 13.31$, $SE = 0.98$) and Self-Both ($M = 13.96$, $SE = 2.38$) groups performed with significantly less AE than the Self-Before group ($M = 23.77$, $SE = 1.85$) and their respective Yoked groups (Yoked-After: $M = 23.06$, $SE = 1.47$; Yoked-Both: $M = 27.80$, $SE = 2.87$); and (2) the Self-Before and the Yoked-Before ($M = 26.18$, $SE = 2.92$) groups were not significantly different.

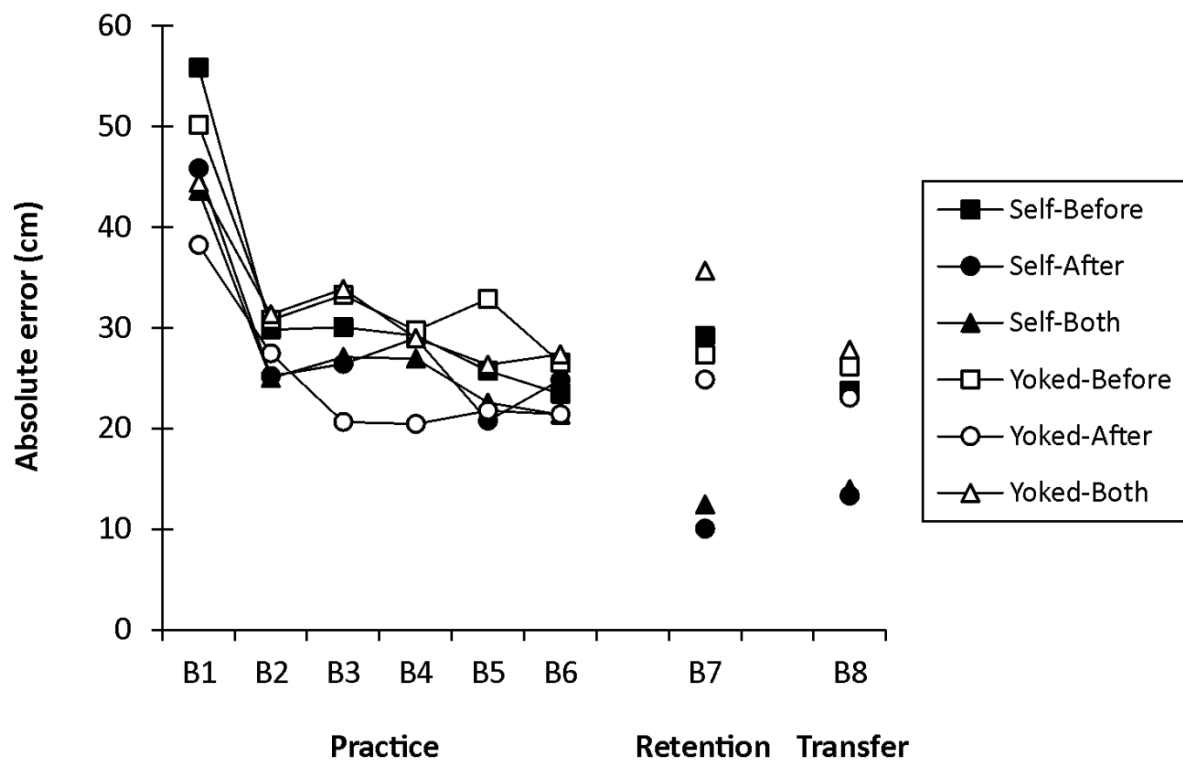


Figure 2.3. Mean absolute error (cm) as a function of choice, decision time, and block (B1 to B6 = practice; B7 = 24-hour retention test; B8 = 24-hour transfer test). Each block includes 10 trials and feedback was only available for blocks 1 to 6.

2.4.2.2. Absolute difference

AD scores for retention and transfer for each group are displayed in Figure 2.4 and were analyzed in separate 2 (Choice) x 3 (Decision) two-way ANOVAs. The main effects for Choice and Decision in retention were superseded by a significant interaction, $F(2, 42) = 7.19$, $p = .002$, $\eta_p^2 = .26$, which revealed that both the Self-After ($M = 10.44$, $SE = 1.40$) and the Self-Both ($M = 13.80$, $SE = 2.59$) groups were significantly more accurate in their subjective performance evaluations than the Self-Before group ($M = 27.01$, $SE = 3.52$). Moreover, the Self-After and the Self-Both groups did not differ significantly but both were significantly more accurate than their respective yoked counterparts (Yoked-After: $M = 22.51$, $SE = 4.16$; Yoked-Both: $M = 29.02$, $SE = 4.32$) whereas the Self-Before group was not statistically different than the Yoked-Before group ($M = 19.37$, $SE = 2.67$).

In transfer, only the main effect for Choice was significant, $F(1, 42) = 19.29$, $p < .001$, $\eta_p^2 = .31$, with post-hoc analysis indicating the Self-controlled groups ($M = 14.68$, $SE = 1.14$) were significantly more accurate than the Yoked groups ($M = 23.67$, $SE = 1.76$). As can be seen in Figure 2.4, this significant main effect for Choice appears to be predominantly driven by the estimations of the Self-After and Self-Both groups. Due to the more accurate estimations in retention and our main interest in comparisons amongst the three self-controlled groups, we conducted a separate one-way ANOVA to examine differences in subjective performance estimations between the three self-controlled groups. The analysis revealed a significant main effect, $F(2, 21) = 5.24$, $p = .014$, $\eta_p^2 = .33$, where post-hoc tests revealed no differences between the Self-After ($M = 12.19$, $SE = 1.86$) and Self-Both ($M = 12.73$, $SE = 1.79$) groups, but both were significantly more accurate than the Self-Before group ($M = 19.12$, $SE = 1.34$).

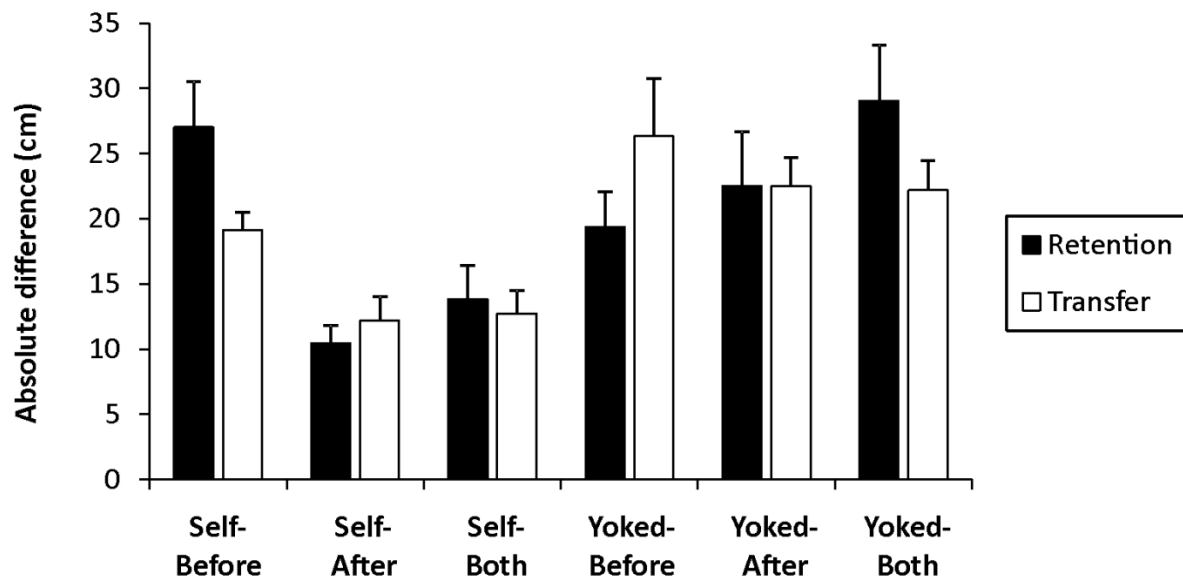


Figure 2.4. Mean (+/-SE) absolute difference (cm) as a function of choice, decision time, and test (Retention = black; Transfer = white). Each test consisted of 10 trials without feedback. Absolute difference was calculated by subtracting the participant's estimated outcome from their actual outcome.

2.5. Discussion

While it has consistently been shown that self-controlled KR schedules enhance motor learning relative to yoked schedules (see Sanli et al., 2013; Wulf, 2007 for reviews), most studies have primarily focused on evaluating the effectiveness of self-controlled KR rather than investigating the relative contributions of motivational and informational processes underlying these learning benefits. The present experiment revisited Chiviawsky and Wulf (2005) with three important modifications: 1) the inclusion of yoked groups (a noted limitation in their design), 2) a dependent measure related to error estimation to examine possible informational benefits of self-controlled KR schedules, and 3) the creation of a novel self-controlled group to test a potential positive additive effect of the posited motivational and informational factors associated with self-controlled KR (see Sanli et al., 2013; Wulf, 2007 for reviews). For this latter purpose, we included three self-controlled groups that were assumed to be reflective of varying levels of informational and motivational contributions. It was thought that the Self-Before group, whose decision to receive KR was restricted to before each trial would gain primarily motivational advantages. In comparison, it was presumed the Self-After group, whose decision was made after each trial, would gain advantages due to informational processes. Advantages due to both motivational and informational processes were expected for our novel Self-Both group that made a KR decision before a trial, but were given the option to change or stay with their original choice after the trial. Our inclusion of yoked groups for all self-controlled groups was a strength of the present experiment and were necessary to understand the proposed contributions of motivational and informational processes to the learning benefits of self-controlled KR schedules.

The present data did not support the hypothesis of a positive additive effect of motivational and informational processes on learning under self-controlled KR conditions. Instead, the critical factor for increased learning appears to be the opportunity to decide after motor execution whether they want

KR. This is because both the Self-After and the Self-Both groups significantly outperformed the Self-Before group in retention and transfer, yet did not differ significantly from one another. Moreover, the Self-After and the Self-Both groups demonstrated significantly more accurate retention and transfer performance compared to their respective yoked groups. In contrast, the Self-Before group showed similar performance to the Yoked-Before group. Thus, simply having control over one's KR schedule prior to motor execution did not result in a learning benefit compared to a corresponding yoked group. These results therefore replicate and extend the work of Chiviacowsky and Wulf (2005) and highlight that self-controlled learning benefits depend on the option of making the KR decision after completing one's motor response.

It is difficult for an explanation based on motivational influences to reconcile why the timing of the KR decision would modulate the learning benefits of self-controlled KR schedules. According to a purely motivational explanation, no differences in motor learning would be expected as all three groups are assumed to have received the same degree of autonomy regarding their choice over when to receive or not receive KR because all self-controlled participants had three KR requests per practice block. Although one limitation of the current study is that no autonomy or motivation measure was collected regarding choice over one's KR schedule⁵, support for our assumption comes from recent work by Ste-Marie et al. (2013) who found learning benefits of self-controlled feedback schedules despite participants in the self-controlled and yoked groups not differing significantly in their perceived choice

⁵ It is important to point out a concern regarding the use of subjective measures for variables such as autonomy and/or motivation in the motor learning domain. Researchers have primarily adopted components of the Intrinsic Motivation Inventory (IMI) (McAuley, Duncan, & Tammen, 1989) to examine these psychological variables (e.g., subscales of interest/enjoyment, perceived choice, perceived competence, and effort/importance). However, a major limitation of using the subscales of the IMI that has not been addressed is that questions are phrased in terms of the task (e.g., taken from Ste-Marie et al., 2013: I enjoyed doing this double mini activity very much) rather than in terms of having control over the variable of interest (e.g., I enjoyed having control over my feedback schedule). Lastly, researchers interested in examining a causal relationship between motor learning and these psychological constructs would require significantly larger sample sizes in order to run the appropriate structural equation modelling analyses.

(i.e., autonomy) or interest/enjoyment (i.e., motivation) throughout practice. Further challenges to the motivational perspective have also emerged in recent years with the finding that limiting or decreasing the amount of self-control opportunities (i.e., a less autonomy supportive context) compared to a traditional self-control group (i.e., a more autonomy supportive environment due to unlimited request opportunities) does not hinder learning (Patterson et al., 2011) and can also lead to superior learning (Hansen et al., 2011). Such findings (see Carter & Patterson, 2012; Patterson et al., 2013 for other examples) suggest that although an autonomy supportive environment afforded by self-controlled KR may contribute to increased motivation and subsequent learning benefits, a more critical factor may be the additional information processing activities engaged during practice.

A question that remains concerns which critical information processing activities are not (sufficiently) engaged when the learner completes their KR decision before, rather than after a motor response? The data from the current experiment support Chiviakowsky and Wulf's (2005) proposition that error estimation is a critical process underlying why self-controlled KR schedules optimize learning when the decision is made after motor execution. This conclusion is based on the superior retention and transfer data (both AE and AD) shown in the present experiment and in recent work by Carter and Patterson (2012). The motor behaviour-memory framework (Kantak & Winstein, 2012), which highlights the importance of encoding processes (e.g., error estimation) during practice for the development of an accurate memory representation would suggest that practicing under conditions where the KR decision is made before a trial (or KR is imposed on the learner without any choice) does not preclude the learner from engaging in error estimation processes. Instead, it seems plausible to suggest any encoding and subsequent learning benefits that can be derived from error estimation are diminished in these practice conditions. For example, KR may be requested (or provided) on a trial where it only provides information that is redundant with response-produced feedback (e.g., Buekers, Magill, & Hall, 1992; Hale & Franks, 1998; Kernodle, Johnson, & Arnold, 2001; Magill, Chamberlin, & Hall, 1991).

Alternatively, KR may not be requested (or provided) for a trial where it would have provided valuable information to strengthen one's memory representation. In fact, research has shown that error estimation during practice is only effective for learning if it is followed by the presentation of KR for that trial (Guadagnoli & Kohl, 2001). In the current experiment, both groups that had the ability to request KR after a trial showed superior performance during retention and transfer. We therefore suggest that having the option to request KR after motor performance allows the learner to request KR only when a comparison between perceived and actual error would maximize the informational value of KR received (i.e., reduce uncertainty because information is transmitted; Fitts & Posner, 1967; Guadagnoli & Lee, 2004; Marteniuk, 1976). An examination of the Self-Both group's behaviour regarding staying or changing their original decision provides support for this contention. Although it was more common for participants to stay with their original choice (108 times for "yes" and 293 times for "no"), there were 30 occasions wherein the KR decision changed from "no" to "yes" and 13 times that it changed from "yes" to "no". Despite these differences, the underlying and crucial similarity of each instance is that no matter the outcome of the second decision, the participants were always able to base their final KR decision following motor execution. This would optimize encoding processes related to the development and strengthening of a more accurate error detection and correction mechanism, which, in the absence of continued motor training, would facilitate the retrieval of a more permanent and adaptable memory representation as measured using retention and transfer tests, respectively (Kantak & Winstein, 2012).

It is interesting to note that during and at the end of practice all groups demonstrated a comparable level of skill proficiency (see Figure 2.3). This is consistent with the extant self-controlled feedback literature (e.g., Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010; Ste-Marie et al., 2013) and highlights the fact these robust advantages do not seem to manifest until a period of no practice has occurred. Two possible explanations may account for this phenomenon in the present experiment and

the self-controlled KR literature in general: motor memory consolidation (Kantak & Winstein, 2012; Robertson, 2009; Robertson, Pascual-Leone, & Miall, 2004) and transfer-appropriate processing (Bransford, Franks, Morris, & Stein, 1979; Lee, 1988; Morris, Bransford, & Franks, 1977).

Consolidation is a set of post-practice (i.e., offline), time-dependent processes that enhance the memory representation that was encoded during practice (Kantak & Winstein, 2012), with these offline improvements thought to be sleep-dependent (e.g., Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; Walker et al., 2003; Walker & Stickgold, 2004). The present data suggest that making the KR decision after a trial resulted in offline improvements (i.e., lower error following the retention interval for the Self-After and the Self-Both groups). Unfortunately, the design of our experiment does not allow a true assessment of offline learning as a comparison between Block 6 and Retention is problematic as these trials were completed under different levels of the independent variable. The inclusion of an immediate retention test would be required to gain better insight into the degree of forgetting and enhancement (i.e., offline learning; see Goh, Sullivan, Gordon, Wulf, & Winstein, 2012; Lin, Fisher, Winstein, Wu, & Gordon, 2008 for examples of this analysis) associated with different self-controlled and yoked KR schedules. Nevertheless, the current data provides initial support that the learning benefits of self-controlled KR schedules (if the decision is made after a trial) are potentially related to enhanced consolidation processes over the retention interval (Robertson et al., 2004; Walker et al., 2002; Walker et al., 2003; Walker & Stickgold, 2004).

Alternatively, the delayed benefits of self-controlled KR schedules may relate to memory retrieval processes. According to the framework of transfer-appropriate processing, learning is optimized when the processing activities promoted by the practice condition resemble the processing activities that are required by the learning tests. Because retention and transfer tests are typically performed without the provision of KR, participants must rely on their error detection and correction mechanism to evaluate and modulate their motor performance on these tests. The encoding processes

associated with strengthening one's ability to detect and correct errors appears to be encouraged when the option to request KR after motor performance is provided. Thus, the superior retention and transfer performance of the Self-After and the Self-Both groups relative to the other experimental groups may also relate to transfer-appropriate processing activities (see Lee, 1988 for a discussion specific to the motor learning domain).

A minor limitation to note in the design of the experiment is the small timing variation in the KR-delay intervals between the groups (see Figure 2.2). The Self-Before group had a fixed 2000 ms before KR would or would not be displayed, while the other two Self-controlled groups had 2000 ms plus the decision time concerning KR delivery. This marginally greater delay between movement completion and KR delivery could be argued to have allowed the engagement of additional error estimation processes to benefit learning that were not available in the fixed 2000 ms interval. However, we specifically adopted a 2000 ms KR delay interval based on past research revealing that error estimation processes are engaged immediately following a movement (Dyal, 1966; Dyal, Wilson, & Berry, 1965; McGuigan, 1959; McGuigan, Crockett, & Bolton, 1960; Newell, 1976; see Salmoni, Schmidt, & Walter, 1984; Swinnen, 1988; Swinnen, Nicholson, Schmidt, & Shapiro, 1990 for in-depth discussions). Therefore, any error estimation processes would be expected to have occurred very quickly following movement completion and well within the fixed 2000 ms KR delay interval used for all groups. As well, although we did not measure KR decision time between the groups, these decisions were made very quickly by participants. Given the above information, we remain confident the learning differences between the Self-After and the Self-Both groups relative to the Self-Before group are related to optimization of the informational value of the KR received rather than to any marginal increases in time between movement completion and KR delivery.

Of final interest was examining whether differences in movement accuracy would emerge between trials where KR was or was not requested. Chiviacowsky and Wulf (2005) reported lower error

scores on KR trials compared to no-KR trials (see also Chiviacowsky & Wulf, 2002). This led to the notion that participants with control over KR may favor receiving KR on more accurate trials as a way to protect perceptions of competence; which in turn enhances learning through motivational factors (e.g., Chiviacowsky, Wulf, & Lewthwaite, 2012). Although our data showed a trend for decreased error on KR versus no-KR trials during the second half of practice (for the Self-After, Self-Both, Yoked-Before, and Yoked-After groups), these differences were not statistically significant (see Table 2.1). As a result, the superior learning of the Self-After and Self-Both groups is difficult to attribute to these participants requesting KR predominantly after more accurate trials as a way to protect perceptions of competence. Chiviacowsky (2014) recently showed that when perceptions of competence associated with KR after successful trials was controlled for between a self-controlled and a yoked group, learning advantages for the self-controlled group still emerged. This further suggests that motivational factors are at best, a minimal contributing mechanism for the learning benefits of self-controlled KR schedules.

Inspection of our data also revealed that participants had greater error on KR trials relative to no-KR trials early in practice; however, later in practice this trend switched (see Table 2.1). This may have been a function of how participants chose to distribute their KR requests within practice blocks (see Table 2.2) as all groups seemed to favour asking for KR on the early trials in a block. This behavioural data, along with subjective KR strategy reports in Carter and Patterson (2012) seem to support an informational role of KR requests early in practice, presumably to help calibrate performance towards the task goal (e.g., Salmoni et al., 1984). In the later blocks of practice, KR may be requested in more of a reinforcement role. That is, KR on more accurate trials may strengthen or help consolidate the learners' memory association between the predicted and actual motor outcomes (Patterson & Carter, 2010).

In conclusion, we investigated whether a positive additive effect of motivational and informational factors was a viable explanation for the learning advantages associated with self-

controlled KR schedules. While the results did not support this additive effect, the robust self-controlled learning advantages did emerge for those participants who had the option to request KR following their performance. We suggest that these advantages were primarily due to encoding advantages associated with the informational value of KR for error estimation processes. The current data support the conclusions of Chiviacowsky and Wulf (2005) that “self-control per se...and perhaps associated increases in motivation...is not the determining factor for the benefits of self-controlled KR” (p. 45). As such, we recommend further investigation into the associated encoding advantages gained from self-controlled KR schedules as the key underlying mechanism for self-controlled motor learning benefits.

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3. Chapter 3

Motor skill retention is modulated by strategy choice during self-controlled knowledge of results schedules¹

¹ A version of this chapter has been accepted:

Carter, M. J., Rathwell, S., & Ste-Marie, D. M. (In Press). Motor skill retention is modulated by strategy choice during self-controlled knowledge of results. *Journal of Motor Learning and Development*. (Accepted Dec 2, 2015).

3.1. Abstract

Investigations into the strategies that are used by participants when they control their knowledge of results (KR) schedule during practice have predominantly relied on multiple-choice questionnaires. More recently, open-ended questions have been used to allow participants to produce their own descriptions rather than selecting a strategy from a predetermined list. This approach has in fact generated new information about the cognitive strategies used by learners to request KR during practice (e.g., Laughlin et al., 2015). Consequently, we examined strategy use in self-controlled KR learning situations using open-ended questions at two different time points during practice. An inductive thematic content analysis revealed five themes that represented participants' unique strategies for requesting KR. This analysis identified two dominant KR strategies: "establish a baseline understanding" in the first half of practice and "confirm a perceived good trial" in the second half of practice. Both strategies were associated with superior retention compared to a yoked group; a group that is unable to engage in KR request strategies because KR is imposed rather than chosen. Our results indicate that the learning advantages of self-controlled KR schedules over yoked schedules may not only depend on *what* strategy is used, but also *when* it is used.

3.2. Introduction

Knowledge of results (KR) is a category of augmented feedback that informs the learner about the outcome of their motor response relative to the task goal. Self-controlling one's KR schedule, defined as self-selecting when to receive or not receive KR during motor training has been shown to facilitate learning compared to conditions wherein the KR schedule is imposed on the learner without any choice (i.e., a yoked condition; see Sanli, Patterson, Bray, & Lee, 2013; Wulf, 2007 for reviews). This superior motor learning has been suggested to result from self-controlled KR schedules allowing participants to tailor their KR schedule to their individual needs on a trial-to-trial basis relative to yoked conditions Chiviacowsky and Wulf (2002). As such, Chiviacowsky and Wulf (2002) concluded that independent of the reasons why KR may be requested for a particular trial, its presentation would be more useful for participants in a self-controlled group because they receive KR when they actually need it; whereas in a yoked group, KR is essentially provided to the participants in a random fashion.

Motor learning scientists have predominantly examined the reasons why participants in self-controlled groups choose to receive KR during practice using multiple-choice questionnaires (e.g., Carter & Patterson, 2012; Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010). For example, after all practice trials were completed for a 4-digit key pressing sequence, Chiviacowsky and Wulf (2002) administered a KR questionnaire to participants in the self-controlled group as well as the yoked group. Participants in the self-controlled group were asked to select the option that best captured their reason for requesting KR during practice. The options referred to whether KR was requested after participants thought they had a good trial, after a poor trial, after good and poor trials equally, or randomly. In contrast, participants in the yoked group were asked to reflect on whether they felt they received KR after the right trials and if they felt they did not, they were asked to identify when they would have wanted to receive KR by choosing one of the previously identified strategies. The questionnaire data for the self-

controlled group revealed a strong preference for participants requesting KR predominantly after they thought they had a “good” trial. For the participants in the yoked group, the majority of them reported that they did not receive KR after the right trials and if given the choice, most of these participants stated they would have preferred to receive KR mostly after what they thought were good trials. This led Chiviacowsky and Wulf (2002) to conclude that self-controlled KR schedules are advantageous for motor learning because they are more congruent with the needs and preferences of the learner compared to yoked KR schedules.

Although the data from these KR strategy questionnaires provided valuable insight regarding how participants use KR when afforded control over their schedule, a limitation of the multiple-choice questionnaires is that participants select a strategy from a predetermined list that is supposed to represent their “own” strategy. More recently, researchers have begun to introduce open-ended questions into their experiments to further our understanding of strategy adoption during practice with a self-controlled feedback schedule (e.g., Aiken, Fairbrother, & Post, 2012; Fairbrother, Laughlin, & Nguyen, 2012; Laughlin et al., 2015). For example, Laughlin et al. (2015) asked participants to elaborate on their reasons for using four different types of instructional assistance, one of which was KR, while learning a 3-ball juggling task. The authors identified three themes for requesting KR: 1) confirm success or improvement, 2) connect technique to performance, and 3) foster confidence or set goals. The strategy of “confirm success or improvement” was the most popular of the three strategies, which parallels the data found in previous studies using the multiple-choice questionnaires (e.g., Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010). The finding that some participants used KR to “connect technique to performance” and to “foster confidence or set goals” represents strategy information that has not been captured in previous self-controlled KR experiments, presumably due to the use of the multiple-choice questionnaires.

Although Laughlin et al. (2015) have shown that open-ended questions can identify new KR strategies, the authors provided very little detail about their qualitative analysis. For example, it is unclear how the themes were identified (e.g., inductively or deductively) and no measure of inter-rater reliability was reported. Nevertheless, a key contribution of Laughlin and colleagues (2015) is that querying participants about their strategies with open-ended questions can be used to identify new reasons for requesting KR, thereby increasing our understanding of why participants request KR when they have control over its scheduling in practice. Similar to Laughlin et al. (2015), we opted to use open-ended questions to query participants on their reasons for requesting KR during practice.

The KR strategy data presented in this paper is a secondary analysis from the practice and learning data that has been reported elsewhere as a function of experimental group (see Carter, Carlsen, & Ste-Marie, 2014). In that experiment, the work of Chiviackowsky and Wulf (2005) was revisited to further investigate the interaction between having control over one's KR schedule and the temporal locus of the KR decision. One self-controlled group made their KR decision before a trial (Self-Before), one made their decision after a trial (Self-After), and another made a decision before a trial but could then decide to stay or change their original choice after a trial (Self-Both). A corresponding yoked group for each of these self-controlled groups were also included. The results revealed superior motor learning in the self-controlled groups that were able to complete their KR decision after a trial (i.e., the Self-After and Self-Both) compared to their yoked counterparts and the Self-Before group. Interestingly, making the decision before a trial afforded no learning advantage as the Self-Before and Yoked-Before groups did not differ significantly on a delayed retention test. It was concluded that a self-controlled KR schedule is only effective for motor learning when the decision is made after a trial because one's self-evaluation of performance can subserve the KR decision, which would maximize the informational value of the KR received (i.e., reduce any uncertainty as information would be transmitted; Fitts & Posner, 1967; Guadagnoli & Lee, 2004; Marteniuk, 1976). Thus, the specific strategies employed by participants

when deciding to request KR may have a strong influence on the usefulness of the KR received and subsequent learning. Along this line, it was recognized that completing the KR decision before motor execution prevents participants from being able to request KR based on a perception of the just completed motor response (e.g., after a perceived good performance); therefore, participants in the Self-Before group were unable to engage in similar strategies to participants in the Self-After and Self-Both groups. Based on this inherent difference in strategy affordance and that the Self-Before group gained no self-controlled learning advantage over their yoked counterparts, it was determined that the Self-Before group would not inform our research question and were therefore excluded from the final analyses in this paper.

In the present paper two phases of analyses were conducted. In Phase One, an inductive thematic content analysis (Braun & Clarke, 2006) was performed on the responses from the open-ended questions to identify emergent themes that represented the participants' unique strategies for requesting KR during the first and second halves of practice. Inductive thematic analysis is a bottom up data driven process that involves coding participants' responses without trying to fit them into pre-existing theoretical notions (Braun & Clarke, 2006). In this sense, by using an inductive approach, participants were given a "voice" to discern their own specific strategies for requesting KR that were guarded against pre-conceptions held by the researchers. In Phase Two, a quantitative analysis was conducted to determine whether motor learning, as measured on a delayed retention test, was differentially impacted by strategy adoption. Specifically, we were interested in whether the dominant strategy of a given practice half, as identified in Phase One, was more effective for retention compared to the other identified strategies (collapsed across each other) and not being able to request KR (i.e., a yoked group). Based on past research (Laughlin et al., 2015; Patterson & Carter, 2010), we expected that a dominant strategy would be requesting KR after trials that were perceived "good" by the learner. We also expected to see a shift in the dominant strategy used between the two halves of practice because it

has been shown that participants in a self-controlled KR group adopt different strategies based on their stage in practice (e.g., Carter & Patterson, 2012). Similar to Laughlin et al. (2015), it was also expected that the use of open-ended questions would reveal strategies for requesting KR that have yet surfaced in the previous self-controlled KR experiments.

3.3. Phase One

It is important to note that the data collection procedures are identical to those reported in Carter et al. (2014) and the reader is directed to that article for specific details not included here.

3.3.1. Methods

3.3.1.1. Participants

Data from sixteen participants (10 females; Mage = 21 ± 0.82 years) were included in the analysis in Phase One. Written informed consent was obtained from all participants and the study was approved and conducted in accordance with the ethical guidelines set by the University's Research Ethics Board.

3.3.1.2. Task and equipment

The goal of the task was to push and release a low-friction slider along a fixed horizontal rail to a target distance of 133 cm. Propelling the slider along the rail required participants to grasp the handle of the slider, then to slowly flex about the elbow joint, then quickly extend their arm and let go of the slider's handle when ready. This task can be likened to a force production task as participants need to learn the correct amount of force to exert for the slider to stop as close as possible to the goal distance. Participants completed this task in the absence of vision (i.e., opaque goggles were worn during all experimental phases) and using their non-dominant hand as assessed using the Edinburgh Handedness Inventory (Oldfield, 1971). End position data of the slider on each trial was captured using a Vernier

Motion Detector 2 (ultrasound frequency of 50 kHz with an accuracy of ± 2 mm within a range of 0.5 to 6 m) that was located at the opposite end to where the participant sat. The motion detector was connected to a Vernier LabPro® that transmitted the position data of the slider to a data collection computer. A customized LabVIEW program (National Instruments Inc.) was created to control the Vernier Motion Detector 2 and the Vernier LabPro, the timing of all experimental stimuli, and to capture and store the end position data for offline analysis.

3.3.1.3. Procedure

Participants were randomly assigned and practiced in one of two self-controlled groups: Self-After and Self-Both. Both groups were told they were free to choose when they would receive KR during practice, but with the restriction they only had three requests per block of 10 trials and that in each block all three requests had to be used. This procedure is identical to that used by Chiviacowsky and Wulf (2005). Importantly, this ensured all participants practiced with a relative KR frequency of 30%, which was necessary to avoid any potential learning differences resulting from differences in KR frequency. Based on their self-controlled group assignment, participants were also informed about when they would be required to complete their KR decision (i.e., told they would be asked either after a trial or both before and after a trial). When KR was provided to the participants, it consisted of the target distance (133 cm), the distance of their attempt (e.g., 140 cm), and their constant error score (e.g., 7 cm).

All participants completed 60 practice trials on Day 1. Upon completion of the third and sixth practice block, the self-controlled participants completed the open-ended question regarding strategy use which asked them to briefly describe “When/Why did you ask for feedback during the previous three blocks of practice trials?” Participants required one to two minutes to write their answer on the

provided sheet of paper and thus, no follow-up questions were asked based on participants' descriptions. Motor learning was assessed using a delayed 24-hour no-KR retention test.

3.3.1.4. Data analysis

An inductive thematic content analysis was used to identify, analyze, and report themes within the data (Braun & Clarke, 2006). For this analysis, the primary coder first read through all participants' responses to the open-ended question and made notes based on the content of the responses. This step in the analysis allows the primary coder to become immersed in the data and familiarized with the depth and breadth of its content. Next, the open-ended responses were analyzed line by line and broken down into codes comprising words, sentences, or entire paragraphs that shared the same idea and/or related to the same topic. For example, the response "If I felt I was getting bad/lazy with my movement" was a segment of text that was considered a code because it represented a single idea. Similarly, the response "I asked when I felt I had undershot or overshoot to see by how much" was also considered a code as it represented a single idea. The next step involved assigning a tag to each code that was relevant to its content. For instance, the code "If I felt I was getting bad/lazy with my movement" was given the tag "Participant asked for feedback because their movement was poor" while the code "I asked when I felt I had undershot or overshoot to see by how much" was given the tag "Participant believed they were off target". Once tags were assigned to each code, they were examined for similarities and grouped together forming higher order themes. For example, the tags "Participant asked for feedback because their movement was poor" and "Participant believed they were off target" were similar and therefore grouped together to form the higher order theme of "Confirm a perceived 'poor' trial", which could also include any other similar tags. The operational definition of each higher order theme, an example of a participant's response for each theme, and the number of responses per theme can be found in Table 3.1. These themes represented participants' unique strategies behind requesting KR during practice.

Table 3.1

The five KR strategy themes (bold and underlined) with its operational definition and an example of a participant's response.

	Count
<u>Establish a baseline understanding</u>	9 – 6
<i>Definition</i> Feedback was requested to obtain a reference for future trials based on how the slider responded to exerted force.	
<i>Example</i> “I asked for feedback on the first trial to gauge the force required to push the object towards the goal distance and to understand how much I needed to adjust”. (Participant 19)	
<u>Evaluate a change in (motor) strategy</u>	5 – 4
<i>Definition</i> Feedback was requested when purposefully changing force or arm configuration to see if a new technique was more successful than the previous trial they received feedback on.	
<i>Example</i> “I would ask for more feedback about 2 tries later [after a baseline strategy request] to see how effective my attempted corrections were”. (Participant 14)	
<u>Confirm a perceived “good” attempt</u>	5 – 7
<i>Definition</i> Feedback was requested because they felt their attempt was successful and wanted to see if they were correct.	
<i>Example</i> “I relied on the way it felt to judge how far I was pushing it. When it felt like I was pushing it the right amount of distance, I would ask for feedback to see if I was getting close”. (Participant 16)	
<u>Evaluate a perceived “poor” attempt</u>	2 – 1
<i>Definition</i> Feedback was requested because they felt their attempt was unsuccessful and wanted to see their amount of error.	
<i>Example</i> “If I felt I was getting bad/lazy with my movement”. (Participant 5)	
<u>Schedule feedback based on trial</u>	6 – 6
<i>Definition</i> Feedback was requested in a way that did not consider force, technique, or accuracy and instead, requests were determined by the spacing of trials.	
<i>Example</i> “I staggered the feedback based on trials to see if I would be more consistent with my throws.” (Participant 5)	

Note. Count represents the total number of responses for each theme as function of practice half (1st – 2nd).

3.3.1.5. Validity

Based on the guidelines outlined by Yardley (2008), the technique of comparing researcher's coding was used during the inductive thematic content analysis to ensure the identified themes that emerged from the data were not imposed by the primary coder. This technique is an external check of the research process that involves the triangulation of coding between two coders (Yardley, 2008). Before the peer analysis occurred, the primary coder coded all responses into individual codes and grouped codes into five themes based on similarity. Next, 52% of the codes were randomly selected and provided to the comparison coder. The comparison coder was also provided with a list of the five identified themes along with the operational definition of each theme. Finally, the comparison coder was instructed to label the codes presented to him to the best of his knowledge using the list of themes and definitions. The primary coder (SR) was an impartial sport psychology doctoral candidate whose area of expertise was in an area unrelated to motor learning (i.e., transformational leadership) and who also specialized in using mixed-methods research. An impartial primary coder was used to ensure the themes were inductively produced, rather than being influenced by predetermined notions or hypotheses based on the extant self-controlled feedback literature. The comparison coder was the first author of this paper. A comparison analysis was performed to determine inter-rater reliability between the two coders and a Cohen's kappa (Cohen's κ) of .90 was calculated. Any value above .80 is considered to represent a strong inter-rater reliability (Hruschka et al., 2004); thus, the primary coder was deemed to be accurately portraying the data.

3.3.2. Results

Five themes were identified (see Table 3.1) that represented participants' unique strategies for requesting KR: 1) establish a baseline understanding , 2) evaluate a change in (motor) strategy, 3) confirm a perceived good trial, 4) confirm a perceived poor trial, and 5) schedule KR based on trial. As

can be seen in Figure 3.1, the dominant self-reported strategy for the first half of practice was "establish a baseline understanding" while the "confirm a perceived poor trial" strategy was the least used. The other three strategies were used to a similar extent during the first half of practice. There was a decrease in the self-reported use of the "establish a baseline understanding" strategy from the first half to second half of practice. This decreased use of that strategy was replaced by an increase in the "confirm a perceived good trial" strategy, which evidently became the dominant strategy during the second half of practice. The self-reported use of the "schedule KR based on trial" strategy also increased in the second half of practice compared to its use in the first half, with a concomitant decrease in both the "evaluate a change in motor strategy" and the "confirm a perceived poor trial" strategy between the two practice halves.

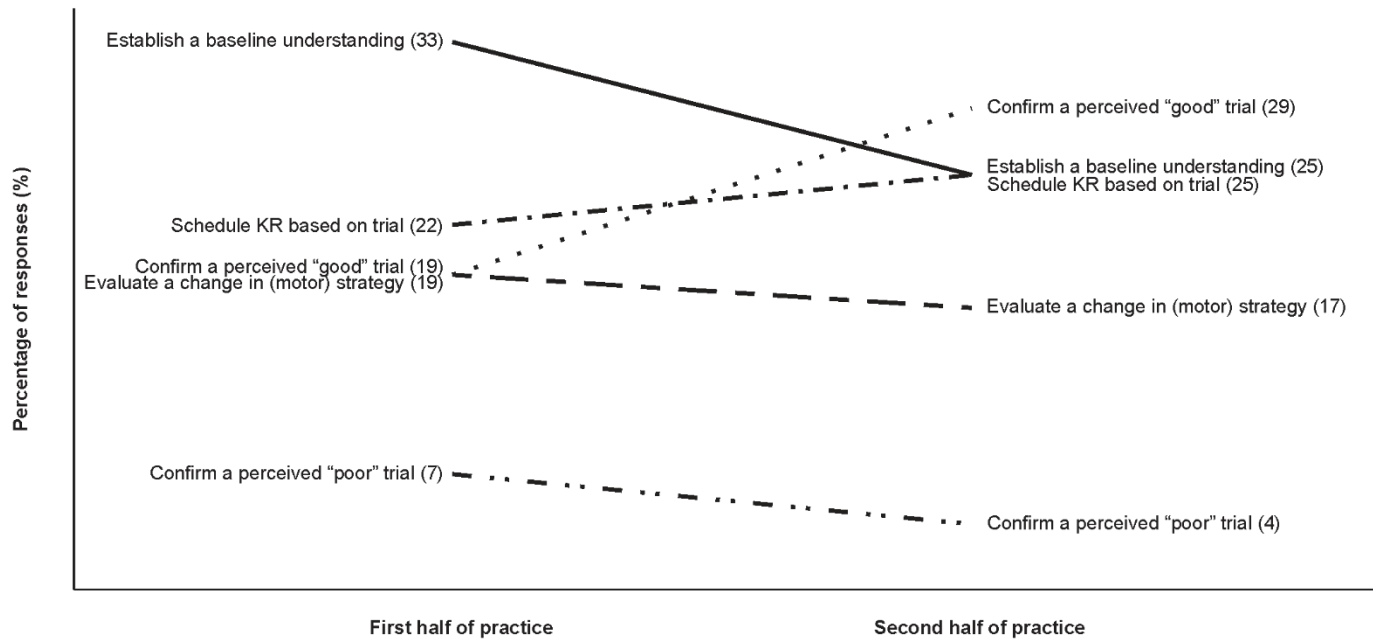


Figure 3.1. Percentage of responses that were coded for each of the five themes for the first (left; trials 1-30) and second (right; trials 31-60) halves of practice. Note the shift in the dominant self-reported strategy (bolded) from “establishing a baseline understanding” (solid line) during the first half of practice to the strategy of “confirming a perceived ‘good’ trial” (dotted line) during the second half of practice.

3.3.3. Discussion

Similar to Laughlin et al. (2015), the use of open-ended questions in the present experiment also identified new strategies for requesting KR such as using KR to “establish a baseline understanding”, to “evaluate a change in (motor) strategy”, and also “scheduling KR based on trial” within a block; thus, extending our current understanding of why participants choose KR during practice. We also noted a shift in the dominant self-reported strategy as a function of practice half, which is consistent with the findings of Carter and Patterson (2012). Specifically, in the second half of practice there was a shift from the “establish a baseline understanding” strategy to the “confirm a perceived good trial” strategy. The identification of the “establish a baseline understanding” strategy is a novel contribution to the literature. We suggest that the propensity of most participants to adopt such a strategy in the first half of practice intuitively makes sense as KR could be used to help participants “get the idea of the movement” (Gentile, 1972) that is required to propel the slider along the rail. Similarly, the “establish a baseline understanding” strategy may have helped familiarize participants with task-intrinsic feedback sources which in turn is important for the development of a reference of correctness for the task (Schmidt, 1975). The use of the “confirm a perceived good trial” strategy is commensurate with past research using both multiple-choice (Chiviakowsky & Wulf, 2002; Patterson & Carter, 2010) and open-ended questions (Laughlin et al., 2015). We suggest this strategy may have served a reinforcement role that helped participants stabilize their performance around the task goal in the later stages of practice (Carter et al., 2014). Alternatively, it is possible that this strategy was used in a similar way to that reported by Laughlin et al. (2015), who found KR was used to enhance motivation and to also set new goals.

The analysis also revealed that a fair number of participants reported requesting KR in a way that did not consider accuracy or technique, and was instead scheduled based on the spacing between trials within a block. It is conceivable that this strategy is a product of restricting the number of KR

requests to three per block as the typical finding with self-controlled KR schedules is that participants fade their KR requests across practice blocks (e.g., Chiviacowsky & Wulf, 2002; c.f. Laughlin et al., 2015). Lastly, the strategy of requesting KR “after perceived poor trials” was the least reported strategy to use across practice halves, which is similar to those reported in past research (Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010) and suggests that most participants are quite capable of labelling trials as “poor” based on task-intrinsic feedback sources.

3.4. Phase Two

The primary question of interest in Phase Two was whether using the dominant KR strategy of a given practice half as identified in Phase One was associated with superior motor learning compared to not using the dominant strategy (i.e., using one of the other four identified strategies) and not being able to use any strategy (i.e., yoked group). Based on the learning results reported in Carter et al. (2014), we included the Yoked-After group as our ‘no strategy’ control group in Phase Two as this was the Yoked group that had the most accurate performance on the delayed retention test; therefore, this group would provide the strongest contrast for our analyses rather than using either of the other lower performing Yoked groups.

3.4.1. Methods

3.4.1.1. Participants

Data from twenty-four participants (15 females; $M_{age} = 21.5 \pm 1.25$ years) were included in the analysis in Phase Two. Written informed consent was obtained from all participants and the study was approved and conducted in accordance with the ethical guidelines set by the University’s Research Ethics Board.

3.4.1.2. Task, equipment, and procedure

Identical to those reported in Phase One but with the addition of the Yoked-After group to represent the 'no-strategy' condition. The participants in the Yoked-After group were paired to a Self-After counterpart and replicated their KR schedule without any choice during practice.

3.4.1.3. Data analysis

To determine whether the dominant KR strategy in each practice half, as identified in Phase One, was associated with superior motor learning compared to all other strategies (collapsed across each other) and a yoked group, two one-way analyses of variance (ANOVA) were conducted on retention performance with Strategy (Dominant vs. All others vs. Yoked) as the between-factor. Differences with a probability of less than .05 were considered to be significant and partial eta squared (η_p^2) is reported to provide an estimate of effect size. Post-hoc analyses were performed using the Fisher's Least Significant Difference (LSD) to determine the locus of any significant differences (Carmer & Swanson, 1973; Saville, 1990).

3.4.2. Results

3.4.2.1. First half of practice

The dominant strategy for the first half of practice was the "establish a baseline understanding" strategy. As can be seen in Figure 3.2A, the "establish a baseline understanding" strategy group ($n = 9$) was more accurate on the delayed retention test compared to the group of participants that did not use this strategy ($n = 7$) and those in the yoked group ($n = 8$), which was supported by a significant main effect, $F(2,21) = 7.061$, $p = .005$, $\eta_p^2 = .402$. Post-hoc comparisons indicated that using the "establish a baseline understanding" strategy ($M = 7.45 \pm 5.22$ cm) resulted in significantly less error than the "all other strategies" group ($M = 17.83 \pm 14.19$ cm) and the no strategy yoked group ($M = 24.88 \pm 8.61$ cm).

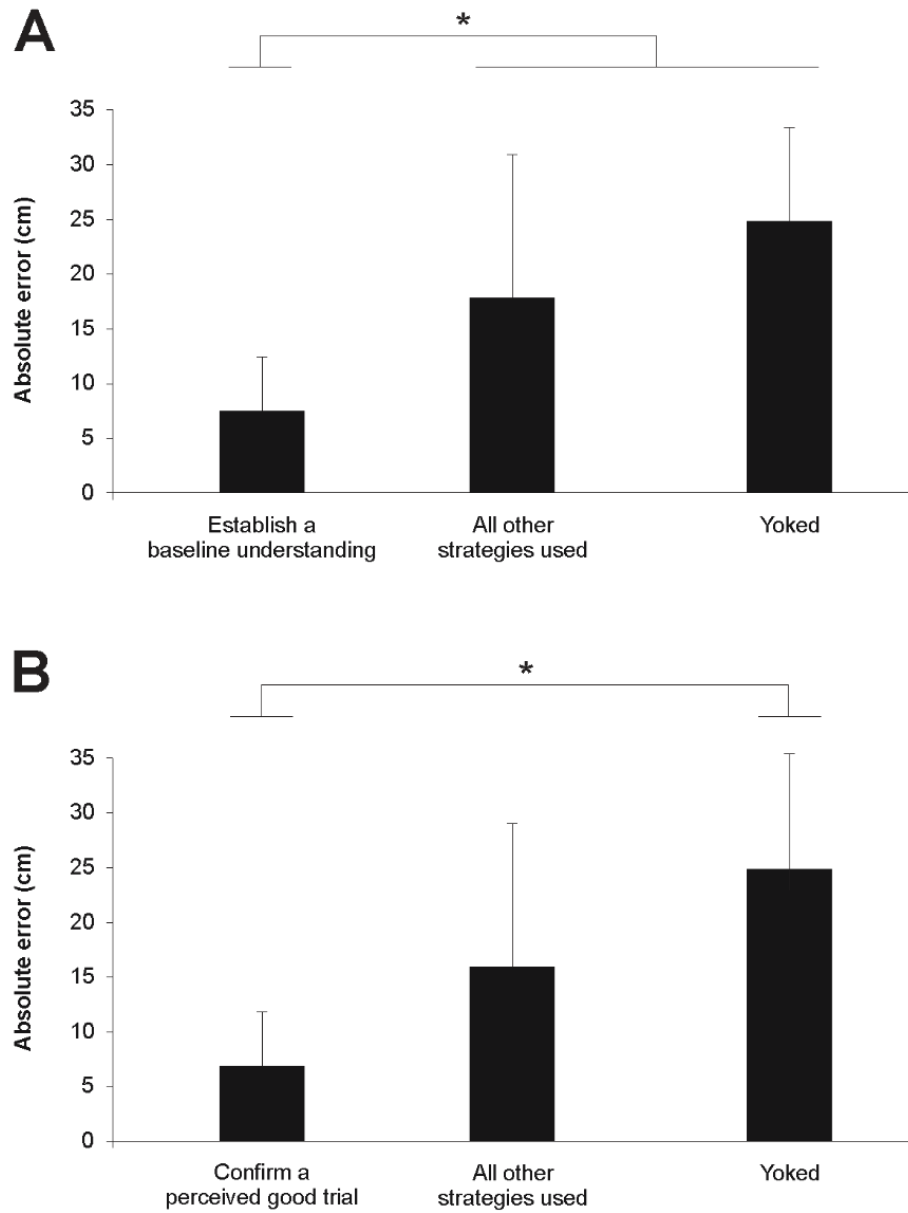


Figure 3.2. Mean (+SE) absolute error on the delayed retention test as a function of KR strategy use during the first (A) and second (B) halves of practice.

3.4.2.2. Second half of practice

The dominant strategy used during the second half of practice was the “confirm a perceived good trial” strategy. As can be seen in Figure 3.2B, there was less error in the “confirm a perceived good trial” strategy ($n = 7$) group compared to the participants that did not use this strategy ($n = 9$) and the yoked group ($n = 8$), which was supported by a significant main effect, $F(2,21) = 6.217$, $p = .008$, $\eta_p^2 = .372$. Post-hoc analyses revealed that the “confirm a perceived good trial” group ($M = 6.87 \pm 5.02$ cm) resulted in significantly less error than the yoked group ($M = 24.88 \pm 8.61$ cm), but was not statistically different than the “all other strategies” group ($M = 15.96 \pm 13.11$ cm).

3.4.3. Discussion

The analysis revealed that motor learning, as measured using a delayed no-KR retention test was differentially influenced by not only the specific KR strategy adopted by the learner, but also the timing of when a particular KR strategy was implemented. Specifically, it was found that the dominant “establish a baseline understanding” in the first half of practice was more effective for skill retention than using any of the other strategies or than that of being in a yoked group. For the second half of practice, the dominant “confirm a good trial” only resulted in significantly more accurate retention compared to practicing in a yoked group. It is important to note however that the difference between this strategy and using any of the other strategies did approach statistical significance ($p = .08$) for enhanced skill retention. Thus, it would appear that engaging in the “confirm a perceived good trial” strategy during the later stages of practice did offer some magnitude of an advantage versus not using this strategy. These findings resonate with the fundamental view that motor learning is a dynamic process (Guadagnoli & Lee, 2004) and consequently the needs of the learner would be expected to vary as practice progresses. The fact that participants exhibited deliberate shifts in their strategy based on the amount of practice completed strongly suggests that self-controlled KR schedules allow participants

to select strategies that maximize the usefulness of the KR received, which in turn has a beneficial effect on learning.

3.5. General discussion

In the present paper we reported the findings from open-ended questions that asked participants in self-controlled KR groups to describe their strategies for requesting KR during the first and second halves of practice while learning a force production task. Previous self-controlled KR experiments have predominantly shared a common limitation of restricting participants to a single response to capture strategy choice and the list of strategies to choose from were predetermined by the researchers (e.g., Chiviakowsky & Wulf, 2002; Patterson & Carter, 2010). Similar to work by Fairbrother and his colleagues (e.g., Aiken et al., 2012; Fairbrother et al., 2012; Laughlin et al., 2015), we used open-ended questions to circumvent this limitation; thus, the qualitative approach used in Phase One is advantageous for two main reasons. First, using an inductive rather than a deductive thematic analysis provides participants with a voice, and therefore, the themes that emerged from this analysis to represent KR strategies were derived from the content of their responses rather than having the researcher(s) impose predetermined strategies. Second, the open-ended questions not only allow for the discovery of new reasons as to why KR was requested, but also strategies that may have been unique to the type of task used and/or the skill proficiency of the learner (e.g., Laughlin et al., 2015). In fact, our analysis not only confirmed previously identified strategies such as using KR to confirm both perceived good and poor trials (e.g., Chiviakowsky & Wulf, 2002), but also identified new strategies which included using KR to “establish a baseline understanding”, to “evaluate a change in (motor) strategy”, and “scheduling KR based on trial” within a block. Moreover, the analysis in Phase Two represents a novel contribution to the literature as it was revealed that adopting certain strategies

appear to be more effective for learning compared to other strategies as measured using a delayed retention tests.

The finding that participants predominantly wanted to use KR to “establish a baseline understanding” is much in line with researchers who have proposed motor learning is a problem-solving process (e.g., Adams, 1971; Gentile, 1972; Guadagnoli & Lee, 2004; Higgins, 1991; Marteniuk, 1976; Schmidt, 1975). In the context of the task used in this experiment, participants needed to learn how much force was required to propel the slider, in addition to the optimal arm orientation to use, grasping style, and/or release point. Indeed, adoption of the “establish a baseline understanding” strategy resonates well with the informational role of KR for the development of a reference of correctness (Salmoni, Schmidt, & Walter, 1984; Schmidt, 1975; Schmidt & Lee, 2011) and what Gentile (1972) described as “getting an idea of the movement” (p. 5). We suggest this KR strategy would therefore be instrumental in helping participants in their search for an appropriate movement configuration (i.e., motor plan) to achieve the task goal as KR used in this way would be expected to help direct the learner’s attention to the relationship between the task goal, their movement, and its associated outcome. Interestingly, the importance of forming a reference of correctness by wanting to know the result of their force output was evident in many of the participants’ responses, for example:

“For the first block I asked for feedback early on to get a sense for how far I was pushing the device” (Participant 6).

“[I] asked to gauge force required to push goal distance when first starting” (Participant 11).

The effectiveness of the “establish a baseline understanding” strategy during the first half of practice was also supported by the quantitative analysis in Phase Two. It was revealed that using this strategy in the first half of practice was associated with significantly less error on the delayed retention test compared to using one of the other four strategies and to a yoked group. Thus, we not only identified a

novel KR strategy in the present experiment, but also demonstrated that the use of this strategy during the early stages of practice has a positive effect on long-term skill retention.

The emergence of the “confirm a perceived good trial” strategy as the dominant strategy during the second half of practice is also similar with Carter and Patterson (2012), as well as the existing self-controlled KR literature when participants identified a KR strategy for practice as a whole (e.g., Chiviacowsky, 2014; Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010; Patterson, Carter, & Sanli, 2011). Despite the robustness of asking for KR after perceived good trials in the self-controlled KR literature, it is interesting that in the present findings this strategy only showed a strong trend ($p = .08$), albeit in the expected direction, for significantly more accurate retention performance than using one of the other four strategies during the second half of practice. To account for this finding, we suggest three alternative explanations.

Firstly, although participants perceived they were requesting KR after “good” trials, their performance on these trials were in fact not more accurate compared to trials when KR was not requested. Such a view is supported by our previously published data (Carter et al., 2014) where the analysis of performance on KR trials versus no-KR trials was not significantly different (see also Carter & Patterson, 2012; Patterson & Carter, 2010); however, others have found performance to be significantly more accurate on KR trials compared to no-KR trials (e.g., Chiviacowsky & Wulf, 2002, 2005; Fairbrother et al., 2012). Secondly, the opportunity itself to strategically request KR and the information-processing activities associated with this process was the key factor for learning compared to the yoked group, which is denied the opportunity to engage in KR request strategies. This notion is consistent with that forward by Chiviacowsky and Wulf (2002) who suggested that independent of the actual KR strategy used, the KR received will always be more useful for participants in a self-controlled group because they receive KR when they actually need/want it. Lastly, if we consider that the typical performance (or learning) curve during the practice phase is a negatively accelerating curve, the largest improvements in

performance occur in the early stages of practice (Bryan & Harter, 1897, 1899; Schmidt & Lee, 2011). From this perspective, the bulk of performance improvements had already occurred in the first half of practice while performance improvements in later stages of practice are known to be more modest.

In the present experiment the number of KR requests provided to learners was restricted to three requests in each block of the 10 trials. As stated in the introduction, this was consistent with the procedures of Chiviawsky and Wulf (2005) and was important to ensure that any differences in learning could be attributed to differences in the amount of KR received during practice (Carter et al., 2014). However, it is possible that this restriction could have impacted how KR strategies were adopted compared to situations where participants are afforded control over KR on all practice trials. Unfortunately, the design of this experiment cannot answer this question; however, Patterson et al. (2011) did report that the percentage of self-controlled KR trials afforded did differentially impact how participants requested KR. In that experiment, the majority of participants in the group with self-control on 100% of trials mostly asked for KR after perceived good and poor trials equally. In contrast, the majority of participants in the two groups with self-control on 50% of trials reported asking for KR mostly after perceived good trials only. Although these groups differed in their self-reported KR strategies, their degree of learning did not differ significantly.

In conclusion, the use of an inductive thematic content analysis in Phase One of the present experiment revealed the use of KR strategies during practice that not only confirmed those of previous experiments (i.e., after perceived good/poor trials; Fairbrother et al., 2012; Patterson & Carter, 2010), but also brought to light new strategies related to the choice for requesting KR. These included the strategies of “establish a baseline understanding”, “evaluate a change in (motor) strategy, and lastly, “scheduling KR based on the trial” within a block of trials. We have also provided novel evidence that motor learning is differentially impacted by the strategy used during the first half of practice. Specifically, participants should use KR early in practice to “establish a baseline understanding” wherein

this strategy is thought to help participants search for the optimal movement configuration to achieve the task goal. Together, the results of the present experiment and those reported by others (e.g., Aiken et al., 2012; Fairbrother et al., 2012; Laughlin et al., 2015) suggest that the use of open-ended questions is an effective way to identify new KR request strategies; thus, it may be fruitful to introduce open-ended questions into practice contexts where learners have control over practice variables other than KR.

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4. Chapter 4

An interpolated activity during the knowledge-of-results delay interval eliminates the learning benefits of self-controlled feedback schedules¹

¹ A version of this chapter has been accepted:

Carter, M. J., & Ste-Marie, D. M. (2016). An interpolated activity during the knowledge-of-results delay interval eliminates the learning advantages of self-controlled feedback schedules. *Psychological Research*. (Epub ahead of print Feb 18, 2016).

4.1. Abstract

The learning advantages of self-controlled knowledge-of-results (KR) schedules compared to yoked schedules have been linked to the optimization of the informational value of the KR received for the enhancement of one's error-detection capabilities. This suggests that information-processing activities that occur after motor execution, but prior to receiving KR (i.e., the KR-delay interval) may underlie self-controlled KR learning advantages. The present experiment investigated whether self-controlled KR learning benefits would be eliminated if an interpolated activity was performed during the KR-delay interval. Participants practiced a waveform matching task that required two rapid elbow extension-flexion reversals in one of four groups using a factorial combination of Choice (Self-Controlled, Yoked) and KR-delay interval (Empty, Interpolated). The waveform had specific spatial and temporal constraints, and an overall movement time goal. The results indicated that the Self-Controlled+Empty group had superior retention and transfer scores compared to all other groups. Moreover, the Self-Controlled+Interpolated and Yoked-Interpolated groups did not differ significantly in retention and transfer; thus, the interpolated activity eliminated the typically found learning benefits of self-controlled KR. No significant differences were found between the two yoked groups. We suggest the interpolated activity interfered with information-processing activities specific to self-controlled KR conditions that occur during the KR-delay interval and that these activities are vital for reaping the associated learning benefits. These findings add to the growing evidence that challenge the motivational account of self-controlled KR learning advantages and instead highlights informational factors associated with the KR-delay interval as an important variable for motor learning under self-controlled KR schedules.

4.2. Introduction

Extrinsic feedback provided to learners that indicates their success in achieving the task goal is termed knowledge-of-results (Schmidt and Young 1991). In the motor learning literature, it is well established that self-controlled KR conditions, operationally defined as permitting the learner control over KR delivery during practice, are more effective for skill retention and transfer compared to conditions wherein the same KR schedule is imposed (i.e., yoked) on the learner without any choice (see Sanli et al. 2013 for a review). As noted by Sanli et al., there are two perspectives forwarded for such findings. On the one hand, these learning advantages have been explained from a motivation-based perspective wherein exercising choice is considered the driving mechanism because having choice is intrinsically rewarding and supports a basic psychological need for autonomy (Chiviawosky 2014; Lewthwaite et al. 2015; Lewthwaite and Wulf 2010; Sanli et al. 2013). On the other hand, an information-processing explanation has been adopted by some researchers who suggest that the opportunity to base the KR decision on one's subjective evaluation of the recently executed motor action (i.e., error estimation) is a critical factor (Carter et al. 2014; Chiviawosky and Wulf 2005). Chiviawosky and Wulf (2005) proposed the importance of error estimation after discovering that the learning advantages of self-controlled KR schedules depended on the timing of the KR decision. Specifically, completing this decision after motor execution was more beneficial for learning a sequential timing task than completing the same decision before motor execution. Such a finding conflicts with the motivation-based explanation as no learning differences between these groups should have been found because both groups had the opportunity to exercise choice over KR delivery.

Carter et al. (2014) recently corroborated and extended the findings of Chiviawosky and Wulf (2005). In their experiment, Carter and colleagues used the two self-controlled groups that differed based on the timing of their KR decision (Self-Before, Self-After) and also added a novel self-controlled

group that made an initial decision before a trial, but could then change or stay with their original choice after the trial (Self-Both). Corresponding no-choice yoked groups for each self-controlled group were included, which addressed a methodological limitation in Chiviacowsky and Wulf's (2005) experiment. The task used required participants to learn the correct amount of force to exert to propel a slider down a rail to an exact distance in the absence of vision. The results revealed superior learning and performance appraisal (i.e., error estimation) abilities in the Self-After and Self-Both groups compared to their yoked groups, as well as the Self-Before group. The Self-Before group did not significantly outperform their yoked counterparts in retention or transfer. In other words, exercising choice over KR delivery before a trial afforded no learning advantage compared to the no-choice Yoked-Before group that was instead told prior to a trial whether KR would or would not be provided. Given that the Self-After and the Self-Both groups did not differ significantly from one another in retention and transfer, or their performance appraisal abilities, Carter and colleagues attributed their enhanced learning to the opportunity to exercise choice regarding KR delivery after a trial (i.e., the common factor between them). It was presumed that the choice after a motor response allowed learners to determine whether receiving KR would be useful based on a subjective performance evaluation of that trial.²

Based on their learning and performance appraisal data, Carter et al. (2014) linked the learning advantages of self-controlled KR schedules to the optimization of the informational value of the KR received for the development of one's error-detection capabilities. This perspective highlights the information-processing activities that encode a motor memory during practice (Kantak and Winstein 2012), with an emphasis on those processing activities engaged during the KR-delay interval. The KR-delay interval refers to the period of time between the completion of a motor response and the presentation of KR for that trial (Schmidt and Lee 2011). With respect to the self-controlled KR research,

²Although this idea was expressed by (Chiviacowsky and Wulf (2005)), the absence of yoked groups in their design posed a challenge for making conclusions regarding the relationship between choice over KR delivery and the timing of this decision with respect to the role of error estimation.

the KR-delay interval culminates in the KR decision. During the KR-delay interval the learner is thought to be actively processing response-produced feedback, which can refer to proprioceptive, visual, auditory, and/or haptic information (Adams 1968; Salmoni et al. 1984; Schmidt and Lee 2011; Swinnen 1988). Simply put, response-produced feedback encompasses any movement-related sensory information that is naturally available in a performance instance, and is therefore highly task-dependent. As such, the KR-delay interval is when the sensory consequences of a movement are processed in working memory so the learner can engage in additional comparative and evaluative processes if KR is provided (Schmidt and Lee 2011). As support for this assertion, it has been demonstrated that motor learning is hindered if the KR-delay interval is filled with an interpolated activity (e.g., Marteniuk 1986; Swinnen 1990) or is eliminated altogether by providing instantaneous KR (e.g., Swinnen et al. 1990). Both of these manipulations are thought to affect a learner's ability to interpret response-produced feedback, albeit for slightly different reasons. For instantaneous KR, it is thought that the immediacy of the KR allots learners no time (or not enough time) to learn to use response-produced feedback to evaluate performance; thus, he or she becomes dependent on using KR to evaluate response outcomes (Swinnen et al. 1990). More relevant to the present study, an interpolated activity is hypothesized to cause structural interference with the normal processing of response-produced feedback upon movement completion as similar high-level learning processes are required by both activities (Swinnen 1990; Marteniuk 1986). Therefore, if Carter and colleagues' (2014) assertion that the learning benefits of self-controlled KR schedules are driven, at least in part, by the optimization of the informational value of the KR as a result of processes engaged during the KR-delay interval, then having learners engage in an interpolated activity during this period would be expected to interfere with these information-processing activities, and thwart the typical self-controlled learning advantages.

The purpose of the present experiment was to test this hypothesis. Thus, two self-controlled KR groups were compared: one that experienced the traditional empty KR-delay interval and one that was required to perform a number-solving task during this interval. A corresponding yoked group was included for both self-controlled groups. If the information-processing activities occurring in the KR-delay interval are not critical for self-controlled KR learning advantages, then learning differences should not be found between the two self-controlled groups, but both should demonstrate superior learning compared to their yoked counterparts. Alternatively, if self-controlled KR learning benefits depend on these information-processing activities then the interpolated activity should eliminate the typical learning advantages of self-controlled KR schedules, and self-controlled learning benefits should only be obtained for the group which did not engage in the interpolated activity. We expected the latter of these two possibilities.

4.3. Methods

4.3.1. Participants and experimental groups

Data were collected from forty-four right-handed (Oldfield 1971) participants with no sensory or motor dysfunctions. Four experimental groups of equal-size were created using a factorial combination of Choice (Self, Yoked) and KR-delay interval (Empty, Interpolated): Self-Controlled+Empty ($M_{age} = 22.27$, $SD = 2.28$ years; 6M, 5F), Self-Controlled+Interpolated ($M_{age} = 22.09$, $SD = 2.30$ years; 6M, 5F), Yoked+Empty ($M_{age} = 22.23$, $SD = 2.94$ years; 7M, 4F), and Yoked+Interpolated ($M_{age} = 22.23$, $SD = 2.94$ years; 5M, 6F). The first 22 participants were randomly assigned to one of the two self-controlled groups while the last 22 participants were randomly assigned to one of the two yoked groups. This assignment procedure is typical in self-controlled KR experiments as the KR schedules of the self-controlled participants are imposed on yoked participants and therefore must be collected first. All participants gave written informed consent prior to inclusion in the studies and the studies were conducted in

accordance with the ethical guidelines of the University and hence with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

4.3.2. Task and apparatus

The task goal was to use elbow extension-flexion movements (2 reversals with specific spatial-temporal constraints) with the non-dominant (left) arm to replicate a target waveform as accurately as possible. The target waveform was created by summing two sine waves: $y(t) = 42\sin(\pi t - 0.3) + 23\sin(3\pi t + 0.4)$. The overall movement time goal was 900 ms during the practice and retention phases. The same waveform was used for the transfer test with the exception that the overall goal movement time was 1150 ms. This waveform task was taken from Goh et al. (2012) and variations of this waveform task have been widely used in the motor learning literature; thus, the task setup and procedures are well-established (e.g., Kovacs et al. 2010; Kantak et al. 2010; Wulf et al. 1993; Goh et al. 2012; Lin et al. 2008).

Participants sat in a chair facing a 22-inch computer monitor with their left forearm resting semiprone in a padded armrest attached to the top of the manipulandum. The manipulandum was affixed to an axis that restricted movement to the horizontal plane. Their elbow was bent at approximately 90° in front of their abdomen and their hand grasped a handle that could be adjusted to ensure the central axis of rotation was about the elbow joint. Vision of the arm was occluded using a felt sheet attached to two wooden levers. A linear potentiometer powered by a 5V direct current power supply attached to the central axis of the manipulandum provided position data which was sampled at 1 kHz for the duration of each movement using analog-to-digital hardware (PCIe-6321, National Instruments Inc.). A customized LabVIEW (National Instruments Inc.) program controlled the timing of all experimental stimuli on each trial, and recorded and stored the data for offline analysis.

4.3.3. Procedure

Prior to the data collection period, all participants had a series of instructions read to them as they followed along on the computer monitor positioned in front of them. In these instructions, all participants were informed of (1) the task and its associated overall movement time goal of 900 ms (no details about the amplitude goals were provided), (2) the manner in which the KR display screen would provide feedback, and (3) how to interpret the KR display. The instructions also explained how KR would be scheduled based on their respective experimental group. Specifically, the self-controlled groups were informed they would get to decide when they wanted KR, but with the restrictions of three requests per block and that all three had to be used. This ensured any learning differences between the groups could not be attributed to discrepancies in the relative frequency of KR. The yoked groups were informed that they would receive KR three times in each block according to a predetermined schedule. The two interpolated groups were also informed that upon movement completion they would be required to perform a number-solving task that required identifying a 2-digit number through trial-and-error (e.g., Marteniuk 1986). Each guess was followed by verbal feedback informing the participant whether each individual digit of their guess was low, high, or good relative to the target number. For example, if a participant guessed “72” and the target number was “38”, the verbal feedback would be “high-low”. Thus on the subsequent guess, the participant would need to guess a number whose first digit was lower than “7” and whose second digit was higher than “2”. Participants were allowed to make as many guesses as possible within the allotted time but always had to wait until feedback regarding the guess was provided before making a new guess. Once a target number was correctly identified, a new 2-digit number had to be discovered. Participants were encouraged to uncover as many numbers as possible during practice and the order of the target numbers was constant across participants.

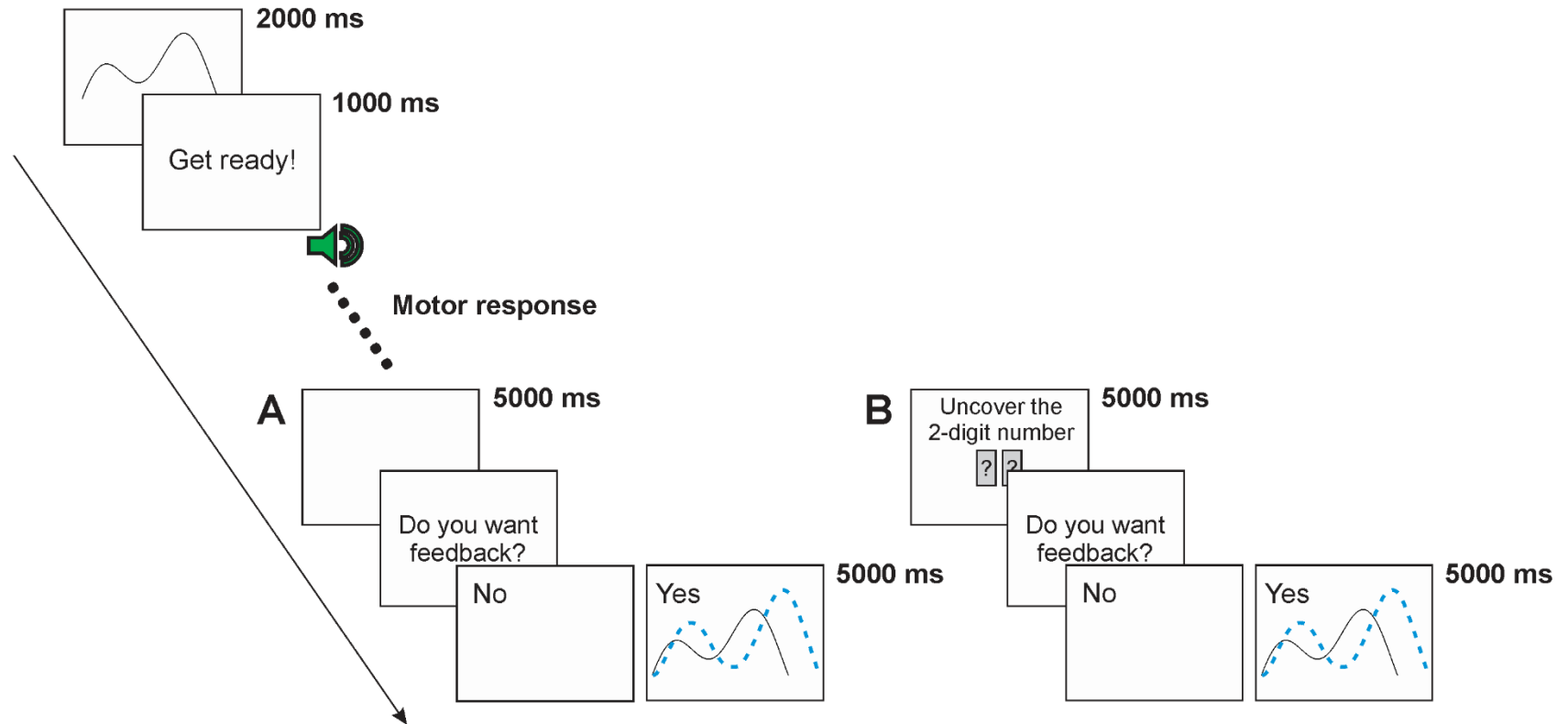


Figure 4.1. Schematic of the temporal events in a typical practice trial for the Self-Controlled+Empty (A) and the Self-Controlled+Interpolated (B) groups. For the respective yoked groups, the only difference in the sequence of events is that the “Do you want feedback?” screen was not displayed to the participants.

An overview of a typical trial is displayed in Figure 4.1. Each trial began with an image of the target waveform displayed (2 s), followed by a visual “Get Ready” and an auditory “Go” signal (1 s apart). Because we were not interested in reaction time, participants were allowed to start their movement when ready following the “Go” signal. The computer screen remained blank throughout the participants’ ongoing movement which results in a more open-loop mode of control (e.g., Kovacs et al. 2010; Leinen et al. 2015; Panzer et al. 2009). Upon movement completion, there was a 5 s interval (i.e., KR-delay interval) that was either empty or filled with the interpolated activity. The interpolated activity only occurred in the practice phase (in retention and transfer, this 5 s interval was empty for all groups). Following this, the KR decision prompt was provided to the self-controlled groups. When KR was provided, it was displayed for 5 s and consisted of a graphic representation of the participant’s movement superimposed on the criterion waveform. On no-KR trials a black screen was displayed for 5 s. As the duration of these events in a typical trial were fixed, the duration of the practice phase was similar between the four groups. The practice phase consisted of six blocks of 10 trials. The retention and transfer tests each consisted of one block of 10 no-KR trials and were performed approximately 24-hours after practice.

4.3.4. Data reduction and analysis

Overall performance accuracy in achieving the target waveform was measured using root mean square error (RMSE). RMSE is the mean difference between the target waveform and the participant’s trajectory calculated over the participant’s actual movement time, and was calculated after synchronizing the onset of the target waveform with the participant’s response (Lin et al. 2010). There are two main advantages of using RMSE: first, it is sensitive to both spatial and temporal errors in the produced motor response relative to the target trajectory, and second, it incorporates both variability and bias of the performed motor response (Kovacs et al. 2010; Schmidt and Lee 2011). RMSE was calculated by the difference between the target waveform and the participant’s response at each data

point in the time series. The differences for each data point in the time series were then squared and the mean of the squared differences computed on a trial basis. Lastly, the square root of the mean was computed for the final measure of RMSE (consistent with Kovacs et al. 2010; Leinen et al. 2015; Lin et al. 2008). Values of RMSE for individual trials were averaged to generate an overall RMSE score for each block of 10 trials. Differences with a probability of $\leq .05$ were considered significant. Partial eta squared (η_p^2) is reported as an estimate of effect size and post-hoc analyses were performed using Tukey's HSD for practice data and Holm-Bonferonni procedures for retention and transfer data. In cases where sphericity was violated, Greenhouse-Geisser adjusted p values are reported.

4.4. Results

4.4.1. Practice

Mean RMSE for each block were analyzed in a 2 (Choice: Self, Yoked) x 2 (KR-delay: Empty, Interpolated) x 6 (Block) mixed-model analysis of variance (ANOVA) with repeated measures on Block. Mean RMSE decreased across practice blocks for all groups (Figure 4.2, left). The significant main effects for KR-delay ($F[1, 40] = 5.730$, $p = .021$, $\eta_p^2 = .125$) and Block ($F[5, 200] = 17.778$, $p < .001$, $\eta_p^2 = .308$) were superseded by a significant Block x KR-delay interaction, $F(5, 200) = 5.343$, $p = .003$, $\eta_p^2 = .118$. Post-hoc analyses revealed that an empty KR-delay interval resulted in greater accuracy in Blocks 3-5 compared to an interpolated KR-delay. The main effect for Choice was also significant, $F(1,40) = 5.730$, $p = .021$, $\eta_p^2 = .125$, with the Self-Controlled groups having lower RMSE than the Yoked groups. The interactions between Choice and KR-delay ($F[1, 40] = 1.935$, $p = .172$), Choice and Block ($F[5, 200] = .157$, $p = .978$), and Choice, KR-delay, and Block ($F[5, 200] = .901$, $p = .482$) were not significant.

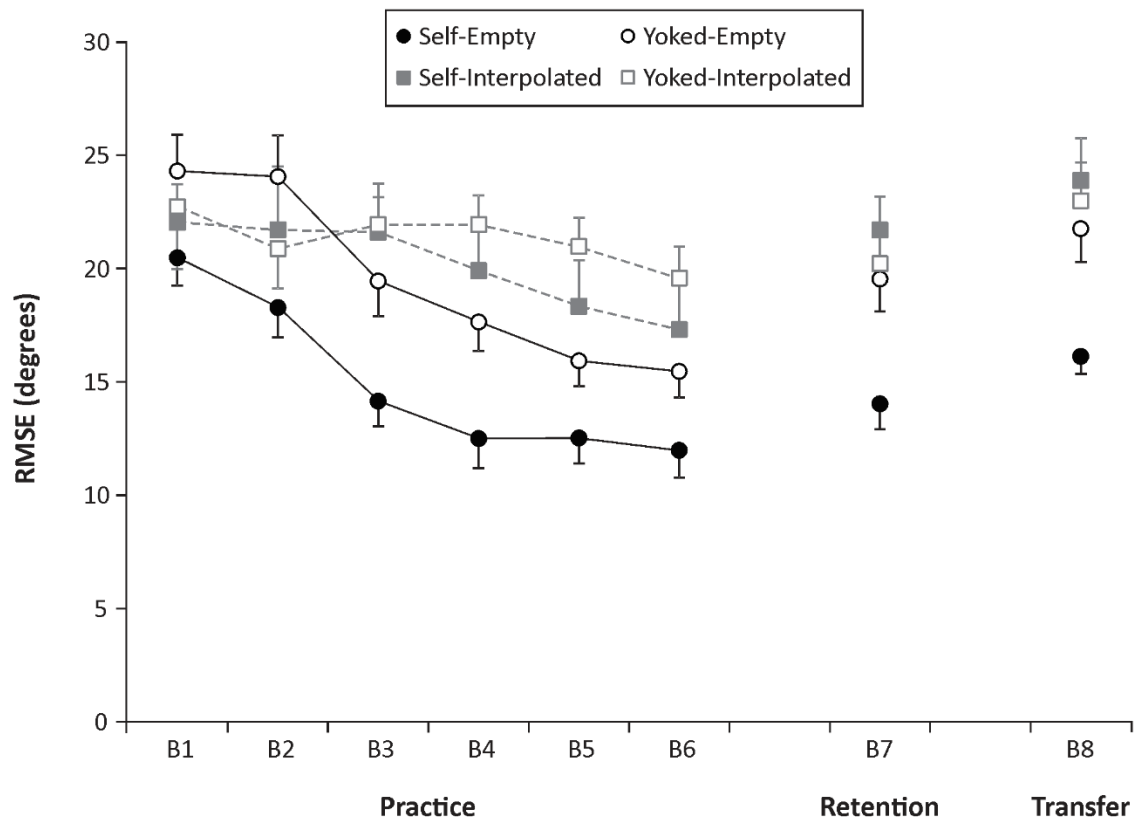


Figure 4.2. Mean RMSE (degrees) for the practice phase (B1-B6) and the 24 hour retention (B7) and transfer (B8) tests. Each block consisted of 10 trials and KR was only available for Blocks 1 to 6. Error bars are standard error.

4.4.2. Retention and transfer

Mean RMSE for retention and transfer were analyzed in separate 2 (Choice) x 2 (KR-delay) two-way ANOVAs. For retention, there was a significant main effect of KR-delay, $F(1, 40) = 8.249$, $p = .006$, $\eta_p^2 = .171$; however, it was superseded by a significant interaction between Choice and KR-delay, $F(1,40) = 5.795$, $p = .021$, $\eta_p^2 = .127$. Post-hoc analyses revealed the Self-Controlled+Empty group was significantly more accurate than the Self-Controlled+Interpolated, Yoked+Interpolated, and Yoked+Empty groups, who did not differ significantly from each other (Figure 4.2, middle). The main effect of Choice was not significant, $F(1, 40) = 1.929$, $p = .172$.

In transfer, there was also a significant main effect of KR-delay, $F(1, 40) = 8.885$, $p = .005$, $\eta_p^2 = .182$, which was superseded by a significant Choice x KR-delay interaction, $F(1,40) = 4.689$, $p = .036$, $\eta_p^2 = .105$. Similar to the retention test, post-hoc analyses revealed that the Self-Controlled+Empty group was significantly more accurate than the Self-Controlled+Interpolated, Yoked+Interpolated, and Yoked+Empty groups, who did not differ significantly from each other (Figure 4.2, right). The main effect of Choice was not significant, $F(1, 40) = 2.465$, $p = .124$.

4.5. Discussion

In the present experiment, we tested Carter and colleagues' (2014) suggestion that information-processing activities during the KR-delay interval, that presumably determine whether receiving KR would resolve any discrepancies between estimated and actual error, is a mechanism underlying self-controlled KR learning advantages. Based on past research, we introduced an interpolated activity during the KR-delay interval (e.g., Marteniuk 1986; Swinnen 1990, 1988) to manipulate the learner's ability to engage in these proposed information-processing activities. Here we show that the typical self-controlled KR learning advantages (see Sanli et al. 2013 for a review) were only found for the Self-Controlled+Empty group relative to their Yoked+Empty counterparts while the Self-

Controlled+Interpolated group did not differ significantly from the Yoked+Interpolated group.

Importantly, the similar retention and transfer performance between the Self-Controlled+Interpolated and the Yoked+Interpolated groups was not merely the result of the interpolated activity making their performance worse as both groups were not significantly different than the Yoked+Empty group in retention and transfer (Figure 4.2). Based on these combined data, we suggest that the interpolated activity interfered with key information-processing activities occurring in the KR-delay interval that are not only inherent to self-controlled KR conditions, but appear to be fundamental for gaining the typically observed learning advantages.

The question to be answered is what key information-processing activities were disrupted during the KR-delay interval? Although the KR-delay interval was viewed originally as an unimportant learning variable (e.g., Salmoni et al. 1984), it has since been reconceptualized as the hub for error-detection/estimation processes (e.g., Swinnen 1990, 1988, 1996; Swinnen et al. 1990). Theoretical and computational accounts of motor control and learning provide some insight regarding the mechanisms of these error-based processing activities (e.g., Adams 1968, 1971; Schmidt 1975a, 1975b; Shadmehr and Krakauer 2008; Wolpert et al. 1998; Wolpert et al. 2011). According to Schmidt (1975b), these activities were subserved by the recognition schema which was thought to generate anticipated sensory consequences of the intended (i.e., planned) motor response. To determine the success of the executed motor response, the learner was hypothesized to compare the anticipated and actual sensory consequences and any perceived discrepancies between them could be confirmed and/or resolved with the provision of KR (Schmidt 1975b). Such a mechanism resonates with forward models of motor control (Miall and Wolpert 1996; Wolpert et al. 1998; Shadmehr et al. 2010; Lee et al. 2016) wherein the forward model creates a predictive sensory signal based on an efference copy of the motor commands for a planned response (akin to that of the recognition schema). This predictive signal is then said to be

used in comparative processing activities in which the actual movement-related sensory information is used to update movements either online or on a subsequent trial should discrepancies be noted.

In the context of self-controlled KR schedules, we suggest it is the result of this comparison between predicted and actual sensory signals that determines whether the learner decides to request KR for a given trial. Support for this notion comes from questionnaire data which have revealed that participants ask for KR in a performance-dependent manner. For example, participants have reported requesting KR after “perceived good trials” (Chiviawsky and Wulf 2002; Patterson and Carter 2010), after “perceived good and poor trials” (Aiken et al. 2012; Patterson et al. 2011; Carter and Patterson 2012), and “to connect performance and technique” (Laughlin et al. 2015). Moreover, participants do not simply use a single KR strategy (Laughlin et al. 2015) and strategy use changes between the first and second halves of practice (Carter and Patterson 2012; Carter et al. accepted). These diverse strategies reveal that participants do not aimlessly request KR and instead are actively estimating their performance based on movement-related sensory information to determine whether KR is needed or not. Chiviawsky and Wulf (2005) were the first to emphasize the importance of error-estimation processes for the learning benefits of self-controlled KR schedules; however, this was only assumed as their design did not include a measure of error-detection capabilities. Carter and Patterson (2012) provided preliminary support for this error-detection hypothesis as they found performance appraisals on a no-KR retention test were more accurate in a younger adult self-controlled group compared to their yoked counterparts (see Carter et al. 2014 for additional support). Given these findings, it seems plausible that practicing with a self-controlled KR schedule concurrently develops more sensitive error-detection capabilities via a forward internal model (i.e., recognition schema) compared to yoked schedules. We further suggest, based on our interpolated activity data, that these superior capabilities are likely developed and refined during the KR-delay interval.

Our finding that an interpolated activity eliminated the robust learning advantages associated with self-controlled KR schedules is likely the result of structural interference (e.g., Marteniuk 1986; Swinnen 1990) with the aforementioned error-detection/estimation processes. This would explain why the Self-Controlled+Interpolated group had similar learning to the Yoked+Interpolated and Yoked+Empty groups, yet diminished learning compared to the Self-Controlled+Empty group. In other words, because the interpolated activity was performed immediately upon movement completion, response-produced feedback (e.g., proprioceptive information) of that response may have gone undetected as information-processing resources were instead directed to the number-solving task. Therefore, the Self-Controlled+Interpolated participants were likely unable to use the actual sensory consequences of their movement in conjunction with their predicted sensory consequences to form a hypothesis regarding the accuracy of their motor response that could be used to subserve the KR decision. This resonates with Carter et al.'s (2014) proposition that self-controlled KR schedules are only effective for learning when a comparison between estimated and actual error is made, which in turn increases the informational value of the KR received (i.e., reduce uncertainty because information is transmitted; Marteniuk 1976; Guadagnoli and Lee 2004). This in turn would help learners develop and refine their performance appraisal abilities via response-produced feedback, which are crucial when the motor task must be performed without the possibility of receiving KR as on delayed retention and transfer tests (Kantak and Winstein 2012).

In conclusion, we investigated the importance of the KR-delay interval for self-controlled KR learning advantages using an interpolated activity. Our results revealed that typical self-controlled KR learning advantages were eliminated in the self-controlled group that had to perform an interpolated activity during the KR-delay interval. The interpolated activity significantly degraded the effectiveness of self-controlling one's KR schedule such that motor learning was comparable to levels found in the two no-choice yoked groups. We suggest this outcome was the result of these learners being unable to

engage in key information-processing activities that contribute to the typically found self-controlled KR learning benefits. Such findings challenge the notion that motivational factors, derived by satisfying fundamental psychological needs through the opportunity to exercise choice, are at the helm of self-controlled KR learning advantages (e.g., Sanli et al. 2013; Lewthwaite et al. 2015). Instead, self-controlled KR learning advantages may stem from the informational value of the KR received being optimized via processes which lead to the development of more effective error-detection capabilities.

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5. Chapter 5

Anodal transcranial direct current stimulation over primary motor cortex does not enhance the learning benefits of self-controlled KR schedules¹

¹ A version of this chapter will be submitted for publication:

Carter, M. J., Carlsen, A. N., Smith, V., & Ste-Marie, D. M. (In Preparation). Anodal transcranial direct current stimulation applied to the primary motor cortex does not enhance the learning benefits of self-controlled feedback schedules.

5.1. Abstract

Although the learning advantages of self-controlled knowledge of results (KR) schedules are well-documented, the brain regions contributing to these advantages remain unknown. Here, we investigated whether applying anodal transcranial direct current stimulation (tDCS) to the primary motor cortex (M1) would enhance self-controlled learning advantages. Participants practiced a rapid arm extension-flexion task in one of four groups using a factorial combination of KR schedule (Self-Controlled vs. Yoked) and tDCS (Anodal vs. Sham). All groups improved their performance in practice; however, no significant differences were found for spatial accuracy in retention or transfer. A significant effect for practicing with a self-controlled KR schedule compared to a yoked schedule was found for temporal accuracy in transfer, but a similar advantage was not evident in retention. The lack of a significant tDCS effect suggests that M1 may not strongly contribute to self-controlled KR learning advantages; however, caution is advised with this interpretation as typical self-controlled learning benefits were not strongly replicated in the present experiment.

5.2. Introduction

A distinct learning advantage has been shown when participants are given choice (i.e., self-control) over knowledge of results (KR) schedules compared to when KR schedules are imposed (i.e., yoked) for both concurrent KR (e.g., Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009; Huet, Jacobs, Camachon, Goulon, & Montagne, 2009) as well as terminal KR (e.g., Chiviacowsky & Wulf, 2002; Patterson & Carter, 2010). Researchers have proposed that this learning advantage arises due to participants in the self-controlled KR group engaging in more effective and effortful information-processing activities during practice than participants in the yoked group (e.g., Carter, Carlsen, & Ste-Marie, 2014; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995; Patterson, Carter, & Sanli, 2011). Support for this proposition comes from varied findings. For example, Post, Fairbrother, and Barros (2011) recorded the amount of time participants took to begin each trial and found that the self-controlled group had significantly longer preparation times than their yoked counterparts; which the authors interpreted as an indicator of more effortful processing activities. Also, Grand et al. (2015) recently tested the notion of more effortful information-processing using electroencephalography and found that the amplitude of the feedback-related negativity (FRN) component of the event-related potential waveform was significantly larger in the self-controlled group compared to the yoked group. This larger negative amplitude suggested that the self-controlled group was engaged in greater, or more effortful, processing of their KR than their yoked counterparts during practice (Grand et al., 2015).

Other researchers have attempted to identify the nature of the information-processing activities being engaged when controlling one's KR schedule. For example, Chiviacowsky and Wulf (2005), and more recently, Carter et al. (2014) have shown that self-controlled KR is only beneficial for learning if the KR decision is made after performing a trial, as compared to before; thus suggesting that

information-processing activities during the KR-delay interval, such as error estimation, may play a decisive role in the observed learning benefits of self-controlled KR schedules. In fact, Carter et al. (2014) found superior error-detection capabilities in retention and transfer in the self-controlled KR groups that made their KR decision after a trial compared to their respective yoked groups, as well as the self-controlled KR group that made their decision before a trial; which was not more accurate than their yoked counterparts. Additionally, others have reported that self-controlled KR learning advantages were eliminated when KR was redundant with task-intrinsic feedback and thus had little-to-no informational value (e.g., Barros, Tran, Aisner, & Salvadora, 2015) or when the interval between the movement and the KR decision (i.e., KR-delay interval) was interposed with a cognitively demanding task (e.g., Carter, Head, Puveendran, & Ste-Marie, 2015). Taken together, such findings make it reasonable to suggest that the effectiveness of self-controlled KR schedules is dependent on the usefulness of the KR received for encoding processes associated with the development and strengthening of error detection capabilities.

If it is accepted that the learning advantages of self-controlled KR schedules are primarily underpinned by information-processing factors, this raises the question regarding what brain regions contribute to these beneficial encoding processes. One possibility is that the primary motor cortex (M1) contributes to self-controlled KR learning advantages. This notion is based on parallels noted with the contextual interference effect in motor learning whereby random practice (as compared to blocked practice) is more beneficial for motor learning (see Lee, 2012 for a review) and that such benefits have been purported to arise from the engagement in more cognitively effortful information-processing activities such as elaborative inter-task comparisons (e.g., Shea & Morgan, 1979; Shea & Zimny, 1988) and/or motor plan (re)construction (e.g., Lee & Magill, 1983, 1985). In a series of experiments conducted by Lin and colleagues (Lin, Fisher, Winstein, Wu, & Gordon, 2008; Lin et al., 2009; Lin, Winstein, Fisher, & Wu, 2010) a single-pulse transcranial magnetic stimulation (TMS) disruption protocol was used to investigate whether the learning benefits of random practice were associated with

processing activities occurring in M1 during the inter-trial interval. When TMS was applied to M1 during practice, the typical learning benefits of random practice were eliminated. Lin and colleagues concluded that information-processing in M1 during the inter-trial interval was important for encoding more permanent motor memories when practicing with a cognitively effortful random schedule compared to the less effortful blocked schedule (Lin et al., 2008; Lin et al., 2009; Lin et al., 2010).

Given the underlying similarities that exist between the proposed information-processing activities responsible for the learning advantages following both random practice and self-controlled KR schedules, and based on the work of Lin and colleagues (Lin et al., 2008; Lin et al., 2009; Lin et al., 2010), it is argued that M1 might also play an important role in the encoding processes and subsequent learning advantages of self-controlled KR schedules. To investigate this proposition, the current investigation applied transcranial direct current stimulation (a-tDCS) over M1 to modulate excitability in this area. tDCS involves passing a small electrical current between scalp-mounted electrodes and anodal stimulation can result in an increase in cortical excitability, as indexed by increases in mean motor evoked potential (MEP) amplitude (Filmer, Dux, & Mattingley, 2014; Nitsche & Paulus, 2001; Stagg & Nitsche, 2011). When anodal-tDCS has been applied over M1, enhanced motor performance and learning has been found for an isometric pinch force task (e.g., Marquez, Zhang, Swinnen, Meesen, & Wenderoth, 2013; Reis et al., 2009), sequence learning (e.g., Cuypers et al., 2013; Kantak, Mummidisetty, & Stinear, 2012; Karok & Witney, 2013; Marquez et al., 2013; Nitsche et al., 2003; Stagg et al., 2011), and hand dexterity tests (e.g., Boggio et al., 2006; Christova, Rafolt, & Gallasch, 2015). Additionally, anodal-tDCS applied over M1 seems to be most effective for performance and learning when stimulation is concurrent with motor training (Stagg et al., 2011). These findings highlight that anodal-tDCS applied over M1, in combination with practice, may provide meaningful information related to its role in the processes governing motor skill learning.

The purpose of the present experiment was to investigate whether anodal-tDCS applied over M1 during practice of a waveform matching task requiring arm extension/flexion would enhance the learning benefits of practicing with self-controlled KR. It was hypothesized that if M1 excitability mediates self-controlled KR learning advantages, then motor skill retention and transfer should be enhanced for the self-controlled group receiving anodal-tDCS compared to the self-controlled group receiving sham-tDCS. Alternatively, if M1 excitability does not significantly contribute to self-controlled KR learning benefits, then no learning differences should be found between the two self-controlled groups. Independent of tDCS, it was expected that both self-controlled KR groups would demonstrate greater learning than their respective yoked group.

5.3. Method

5.3.1. Participants

Data were collected from forty-four individuals ($M_{\text{age}} = 20.73$, $SD = 1.58$; M/F = 20/24) that were recruited from the University's undergraduate and graduate student population. All participants were right-handed as determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The experiment was approved by and conducted in accordance with the ethical guidelines set by the Health Sciences and Science Research Ethics Board at the University of Ottawa and conformed to the latest revision of the Declaration of Helsinki.

5.3.2. Task and apparatus

The task goal was to use extension-flexion movements about the elbow of the non-dominant (left) arm to replicate a criterion waveform as accurately as possible (see Figure 5.1). As greater learning effects are seen when participants use their non-dominant arm (Stockel & Weigelt, 2012), the left arm was placed in a custom manipulandum that allowed measurement of movement about the elbow in the horizontal plane. The motor task consisted of two rapid elbow extension-flexion reversal movements

with specific amplitude and temporal constraints, and an overall movement time goal of 900 ms (during the practice and retention phases). For the transfer test the same waveform shape was used, but the overall goal movement time was increased to 1150 ms. Variations of this task have been successfully used by motor learning researchers investigating the effects of non-invasive brain stimulation techniques on motor memory encoding and consolidation processes (e.g., Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010; Lin et al., 2009).

Participants sat in a chair facing a 22-inch computer monitor with their left forearm resting semiprone in a padded armrest attached to the top of the manipulandum. The starting position required participants to have their elbow bent at approximately 90° in front of their abdomen with their hand grasping a handle that could be adjusted to ensure the central axis of rotation was collinear with the elbow joint, and vision of the arm and the manipulandum were occluded. A linear potentiometer powered by a 5V direct current power supply attached to the central axis of the manipulandum provided position data which was sampled at 1000 Hz for the duration of each movement using analog-to-digital hardware (PCIe-6321, National Instruments Inc.). A customized LabVIEW (National Instruments Inc.) program controlled the timing of all experimental stimuli on each trial, and recorded and stored the data for offline analysis.

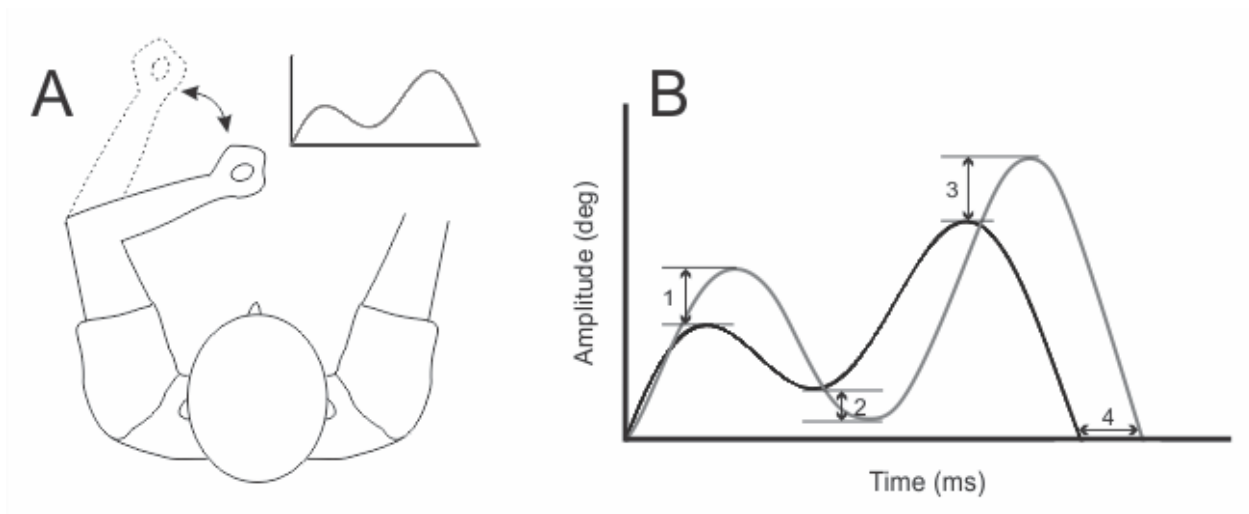


Figure 5.1. (A) Top-down view of participant setup and the criterion waveform that participants had to match by performing two rapid elbow extension-flexion reversals. (B) Spatial accuracy was quantified by summing the absolute constant error at each reversal point which are represented by numbers 1 through 3 ($|CE| - \sum_{Amp}$). Temporal accuracy was quantified as the absolute constant error in movement time with respect to the goal time which is represented by number 4 ($|CE|_{MT}$).

5.3.3. Procedure

Upon arrival to the laboratory, participants read and signed an informed consent sheet before completing a non-invasive brain stimulation screening questionnaire (Rossi, Hallett, Rossini, Pascual-Leone, & Group, 2009). The first 22 participants were randomly assigned to one of the two self-controlled groups, while the last 22 participants were randomly assigned to one of the two yoked group, resulting in four experimental groups: Self-Controlled with anodal-tDCS (hereafter Self-Anodal), Self-Controlled with sham tDCS (hereafter Self-Sham), Yoked with anodal-tDCS (hereafter Yoked-Anodal), and Yoked with sham tDCS (hereafter Yoked-Sham). Sham tDCS groups were included to control for any possible effects from the presence of the electrodes on the scalp and the initial tingling sensation that is felt during the ramping up phase at the onset of stimulation.

All participants completed 80 practice trials (8 blocks of 10 trials) of the waveform matching task on Day One. For the practice phase, the self-controlled groups were informed that they would have the opportunity to choose whether they wanted to receive KR after a trial, but with the restriction they would only have three KR opportunities per block of 10 trials and that all three had to be used. Once all three requests had been used in a block, the KR decision prompt was no longer displayed after a trial. This ensured all participants practiced with a relative KR frequency of 30% and therefore, any learning differences between groups could not be attributed to receiving different amounts of KR. The yoked groups were told that KR would be provided three times in each practice block based on a predetermined schedule.

Each trial began with the goal waveform displayed for 2 s, followed by a visual “Get Ready” and then an auditory “Go” signal (1 s apart). Participants were informed that they were allowed to start their movement when ready following the “Go” signal, but that it was not a reaction time task. No visual feedback was provided during the motor responses, which is thought to encourage a more preplanned

(i.e., open-loop) mode of control (e.g., Kovacs, Boyle, Grutmacher, & Shea, 2010; Leinen, Shea, & Panzer, 2015; Panzer, Krueger, Muehlbauer, Kovacs, & Shea, 2009). For the self-controlled groups, a KR decision prompt was displayed 3 s following the end of movement (if KR trials remained unused in a block), whereas the yoked groups experienced the same 3 s interval but with a blank screen. On KR trials, KR was displayed for 5 s and consisted of a graphic representation of the participant's displacement trace superimposed on the goal waveform. On no-KR trials, a blank screen was displayed for 5 s. Approximately 24-hours after completing the practice phase, participants returned to the laboratory and performed delayed retention and transfer tests (both one block of 10 trials) without KR.

5.3.4. Transcranial direct current stimulation

tDCS (1 mA, current density = 0.128 mA/cm² at the active electrode) was administered for 18 minutes during the practice phase using a Dupel iontophoresis constant current delivery device (Empi) connected to a pair of electrodes. The active electrode (sponge electrode, 1.5 ml, 7.8 cm²; Ionto+) was saturated with sterile saline (0.9% NaCl) to create a conducting medium between the electrode and the scalp. A large reference electrode (carbon foam, 39 cm²; Ionto+) was used as the larger surface area allowed the current density to be sufficiently low such that it would have a negligible effect on underlying cortical areas (Nitsche et al., 2008). The active electrode was centered over electrode site C4 of the International 10-20 EEG system using the procedures outlined by DaSilva, Volz, Bikson, and Fregni (2011) wherein 20% of the auricular measurement was calculated and this value (~ 4 cm) was then measured from Cz through the auricular line. Neuroimaging studies have shown that C3/C4 correspond to the scalp locations directly over left and right M1, respectively (Okamoto et al., 2004). This spot has been used successfully in previous experiments to elicit behavioral changes following tDCS applied to the right M1 (e.g., Cogiamanian, Marceglia, Ardolino, Barbieri, & Priori, 2007; Tecchio et al., 2010). The reference electrode was positioned over the contralateral supraorbital ridge (Reis & Fritsch, 2011; Reis et al., 2009). Both electrodes were self-adhesive, but additional foam underwrap was used to hold the

electrodes in place, thereby ensuring optimal contact throughout stimulation. For anodal stimulation, the active electrode was the relative positive terminal where positive current flowed into the body and the reference electrode was the relative negative terminal where the positive current then exited the body (DaSilva et al., 2011). For the sham tDCS groups, the stimulator was only powered on while ramping up to 1 mA (~ 15 s) and was then immediately shut off without the participant's awareness. Past research has shown that participants are unable to detect a difference between real and sham stimulation with this procedure (Gandiga, Hummel, & Cohen, 2006). All participants tolerated the tDCS very well and no adverse effects were reported.

5.3.5. Dependent measures and statistical analyses

Given that the goal waveform had specific spatial and temporal requirements, separate measures for spatial and temporal accuracy were used. Consistent with the procedures of Lin et al. (2009), temporal accuracy was quantified using absolute constant error ($|CE|$) of movement time with respect to the goal time ($|CE|_{MT}$; see Figure 5.1) and spatial accuracy was quantified using the sum of $|CE|$ in movement amplitude for each reversal point in the movement trajectory ($\sum |CE|_{Amp}$; see Figure 5.1). For the practice phase, mean $\sum |CE|_{Amp}$ and $|CE|_{MT}$ were analyzed using separate 2 (KR schedule: Self, Yoked) x 2 (tDCS: Anodal, Sham) x 8 (Block) mixed-model analyses of variance (ANOVA) with repeated measures on Block. For the retention and transfer tests, mean $\sum |CE|_{Amp}$ and $|CE|_{MT}$ were analyzed using separate 2 (KR schedule) x 2 (tDCS) two-way ANOVAs. Differences with a probability of $\leq .05$ were considered significant and partial eta squared (η_p^2) is reported as an estimate of effect size. Post-hoc analyses were performed using Tukey's HSD and in cases where the assumption of sphericity was violated, Greenhouse-Geisser adjusted p values are reported.

5.4. Results

5.4.1. Spatial accuracy

5.4.1.1. Practice

$\sum |CE|_{\text{Amp}}$ decreased across practice blocks for all groups (Figure 5.2), which was supported by a significant main effect for Block, $F(7, 280) = 25.581$, $p < .001$, $\eta_p^2 = .390$. However, this was superseded by a significant tDCS x Block interaction, $F(7, 280) = 4.95$, $p < .001$, $\eta_p^2 = .110$. Post-hoc analyses revealed that Block 1 was significantly less accurate than Block 4 and Blocks 6 through 8 for the participants that received anodal-tDCS and that Blocks 1 and 2 were significantly less accurate than Blocks 2 through 8 and Blocks 4 through 8, respectively, for the participants that received sham-tDCS. In addition, spatial accuracy in Block 1 for sham-tDCS participants was significantly less accurate than Blocks 1 through 8 of the anodal-tDCS participants. Block 2 for the participants that received sham-tDCS was significantly less accurate than Blocks 4 through 8 of the participants that received anodal-tDCS. Although there was a trend for a difference between anodal-tDCS and sham-tDCS in the expected direction ($p = .08$), this difference failed to reach conventional levels of significance. All other main effects and interactions were not statistically significant (p values $> .05$).

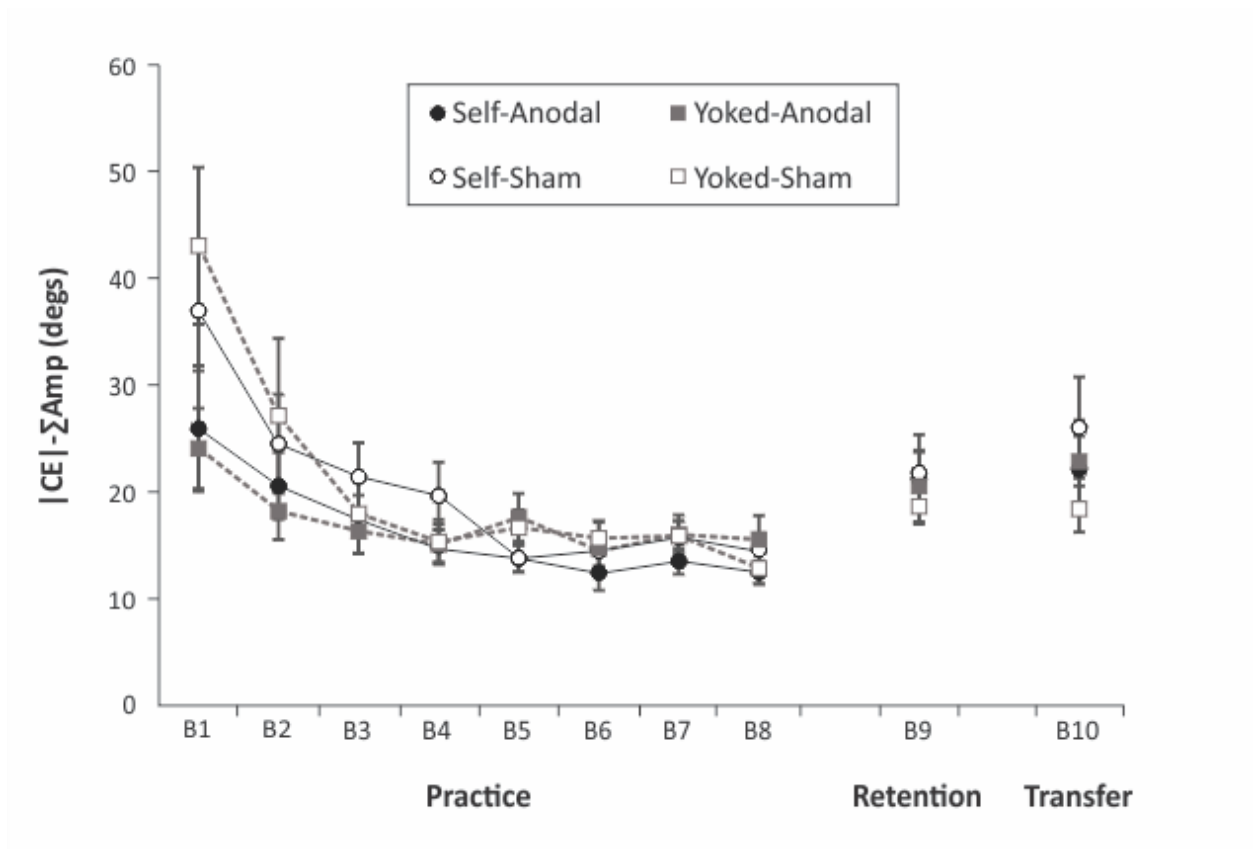


Figure 5.2. Mean $|CE| - \Sigma Amp$ ($\pm SE$) for the practice phase (B1-B8) and the 24 hour retention (B9) and transfer (B10) tests. Each block consisted of 10 trials and KR was only available during Blocks 1 through 8.

5.4.1.2. Retention

$\sum |CE|_{\text{Amp}}$ did not differ significantly between the groups (Figure 5.2) and the analysis revealed that neither the main effects of KR schedule, $F(1, 40) = .434$, $p = .51$, or tDCS, $F(1, 40) = .052$, $p = .82$, nor the interaction of these factors, $F(1, 40) = .189$, $p = .67$, were statistically significant.

5.4.1.3. Transfer

Similar to retention, no significant differences were found (Figure 5.2) and neither the main effects of KR schedule, $F(1, 40) = .564$, $p = .46$, or tDCS, $F(1, 40) = .036$, $p = .85$, nor the interaction of KR schedule and tDCS, $F(1, 40) = 2.223$, $p = .14$, reached statistical significance.

5.4.2. Temporal accuracy

5.4.2.1. Practice

Mean $|CE|_{\text{MT}}$ decreased across practice blocks for all groups (Figure 5.3), which was supported by a significant main effect for Block, $F(7, 280) = 17.147$, $p < .001$, $\eta_p^2 = .300$. Post-hoc analyses revealed that timing error was significantly greater in Block 1 compared to Blocks 2 through 8. All other main effects and interactions were not statistically significant (p values $> .05$).

5.4.2.2. Retention

Temporal accuracy was not significantly different between the groups (Figure 5.3) and neither the main effects of KR schedule, $F(1, 40) = 1.273$, $p = .27$, or tDCS, $F(1, 40) = .046$, $p = .83$, nor the interaction of KR schedule and tDCS, $F(1, 40) = 1.881$, $p = .18$, reached statistical significance.

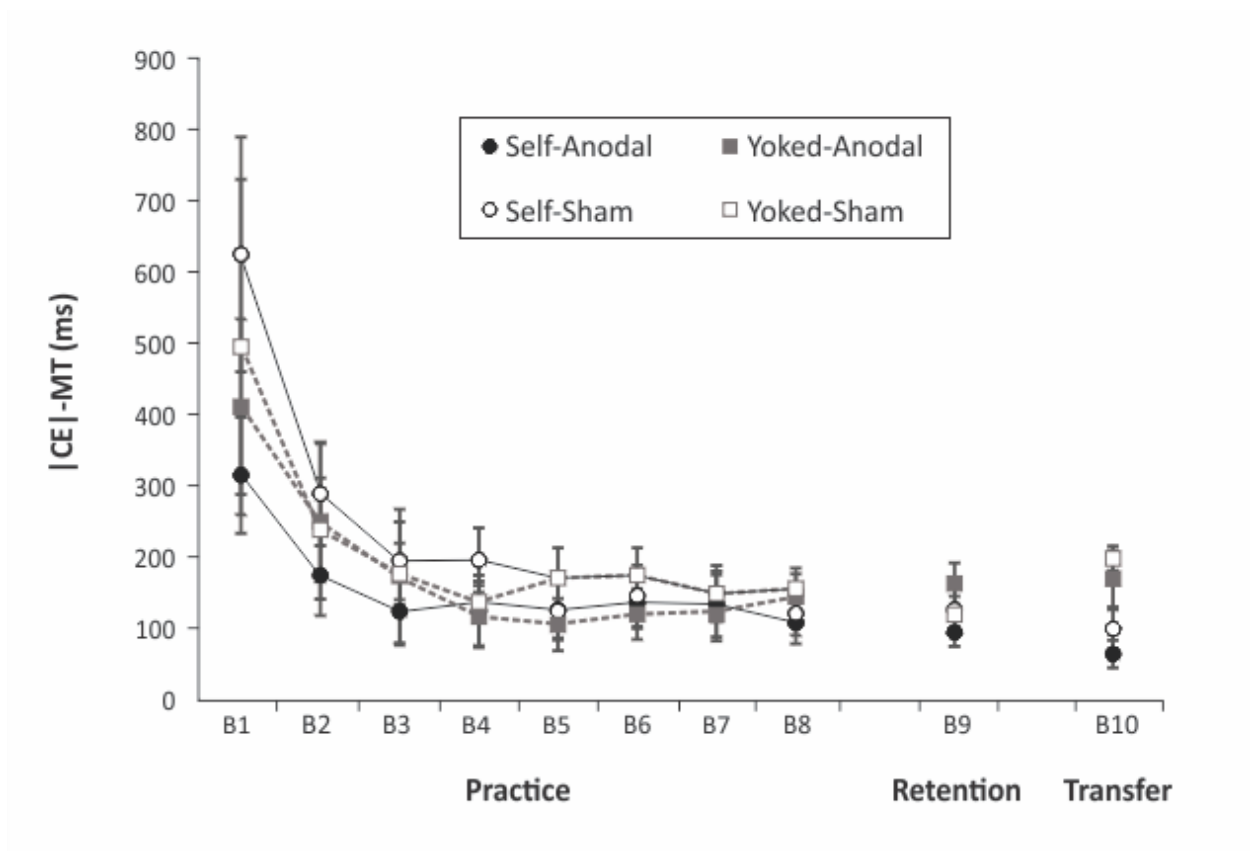


Figure 5.3. Mean $|CE|_{MT}$ ($\pm SE$) for the practice phase (B1-B8) and the 24 hour retention (B9) and transfer (B10) tests. Each block consisted of 10 trials and KR was only available during Blocks 1 through 8.

5.4.2.3. Transfer

A significant main effect of KR schedule was found for $|CE|_{MT}$, $F(1, 40) = 13.981$, $p = .001$, $\eta_p^2 = .259$, whereby the self-controlled KR groups demonstrated greater accuracy relative to the yoked KR groups (Figure 5.3). All other comparisons failed to reach statistical significance (p values $> .05$).

5.5. Discussion

Although the effectiveness of self-controlled KR schedules compared to yoked KR schedules is well-documented in the motor learning literature, the brain regions contributing to these learning benefits remain unclear. In the present experiment, we examined whether applying anodal-tDCS over the arm region of M1 concurrently with practice would enhance the learning benefits of self-controlled KR schedules. Contrary to this prediction, the results showed that the Self-Anodal and the Self-Sham groups' retention and transfer performance did not differ significantly for either spatial or temporal accuracy. We also anticipated that practicing with a self-controlled KR schedule, independent of tDCS, would result in superior learning than practicing with a yoked KR schedule. This prediction was partially supported as the self-controlled KR groups demonstrated less timing error in transfer, but not for retention. Moreover, no significant effect of KR schedule was found for spatial accuracy in retention or transfer.

Although we had expected self-controlled KR learning advantages to emerge in both retention and transfer, our finding that the self-controlled KR groups were only significantly more accurate in generalizing their learning to a novel transfer task variation than the yoked groups is consistent with past self-controlled KR research (e.g., Chiviawsky & Wulf, 2002; Fairbrother, Laughlin, & Nguyen, 2012; Grand et al., 2015; Hansen, Pfeiffer, & Patterson, 2011). The trend of self-controlled KR learning benefits occurring only in transfer has led some researchers to suggest that transfer tests may be a more sensitive measure of learning than retention of a previously practiced skill (e.g., Chiviawsky & Wulf,

2002, 2005). Others, however, have attributed their self-controlled KR learning advantages specific to skill transfer to the idea that such benefits are related to self-evaluation which strengthens the ability to effectively adapt or scale performance to novel task requirements (Fairbrother et al., 2012). In fact, past research (Carter et al., 2014; Carter & Patterson, 2012) has demonstrated that self-controlled KR schedules result in more accurate error estimation capabilities compared to yoked schedules; however, this was found in both retention and transfer. As such, it currently remains unclear why sometimes self-controlled KR learning advantages only emerge in transfer as in the present experiment, whereas these learning benefits are apparent in both retention and transfer in other experiments (e.g., Patterson & Carter, 2010; Patterson, Carter, & Hansen, 2013).

To our knowledge, our experiment was the first to incorporate a neurostimulation technique in a self-controlled KR experiment to examine whether M1 contributes to the well-known learning advantages of self-controlled KR schedules over yoked KR schedules. We did not find a significant effect for tDCS in either retention or transfer which suggests that M1 may not be strongly implicated in the learning benefits associated with self-controlled KR schedules. The lack of a significant effect for tDCS is not consistent with past motor learning research where beneficial online (i.e., during practice) and/or offline (i.e., consolidation) effects of anodal-tDCS applied over M1 concurrently with motor training have been reported (Christova et al., 2015; Kantak et al., 2012; Nitsche et al., 2003; Prichard, Weiner, Fritsch, & Reis, 2014; Reis et al., 2009; Stagg et al., 2011). One reason for this inconsistency in findings may relate to how motor performance and learning were quantified in the present experiment compared to previous experiments. Specifically, learning benefits of tDCS have typically been inferred based on pre- and post-tDCS differences in reaction and/or movement time (e.g., Christova et al., 2015; Kantak et al., 2012). The fact that differences are found using these two measures is not surprising from a neural activation perspective (Carlsen, Maslovat, & Franks, 2012; Hanes & Schall, 1996) given anodal-tDCS has been shown to increase cortical excitability (Nitsche & Paulus, 2001); thus, the time required to further

raise activation over an initiation threshold would be reduced compared to sham-tDCS. In contrast, motor learning was evaluated in the present experiment with respect to the memorial quality of matching specific amplitude goals and an overall timing goal. As such, our findings suggest that the effectiveness of tDCS for optimizing motor learning may, in part, depend on the measures used to quantify learning.

A final consideration relates to the brain region that was targeted in the present experiment. Although past research has shown that M1 is involved in the formation and retention of memory representations of recently acquired motor skills (Hadipour-Niktarash, Lee, Desmond, & Shadmehr, 2007; Lin et al., 2008; Lin et al., 2009; Lin et al., 2010; Muellbacher et al., 2002), in the context of self-controlled KR schedules, M1 may not be a primary brain region contributing to the learning advantages. While debate exists as to why self-controlled KR schedules enhance motor learning (for a discussion see Sanli, Patterson, Bray, & Lee, 2013), some researchers have highlighted the importance of KR processing and error-detection capabilities in reaping self-controlled KR learning benefits (Carter et al., 2014; Fairbrother et al., 2012; Grand et al., 2015). As such, it may be more appropriate for future studies to target brain areas that have been implicated in the integration of sensory information for response evaluation and/or planning processes such as the cerebellum (Criscimagna-Hemminger, Bastian, & Shadmehr, 2010), the posterior parietal cortex (Della-Maggiore, Malfait, Ostry, & Paus, 2004), and the supplementary motor area (Stock, Wascher, & Beste, 2013).

In conclusion, a significant role for M1 in the learning benefits of self-controlled KR schedules was not found in the present experiment using anodal-tDCS. Although continued investigations regarding important brain regions is encouraged in the self-controlled motor learning literature, it may be more fruitful for these future studies to use more focal forms of non-invasive brain stimulation such as TMS and HD-tDCS (Kuo et al., 2013). A better understanding of the relevant brain structures and their

associated functions would prove valuable for our understanding of why self-controlled KR schedules enhance learning at a theoretical level.

5.6. References

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6. General discussion

In the self-controlled versus yoked KR research protocol, both groups receive KR in the same temporal order of trials and for the same absolute amount; thus, the observed learning advantages of self-controlled KR schedules have been argued to arise from having control (i.e., choice) over KR. Some researchers have suggested this opportunity to exercise choice results in motivational influences that enhance learning through a satisfaction of the fundamental psychological needs of autonomy and competence (e.g., Lewthwaite, Chiviakowsky, Drews, & Wulf, 2015; Sanli, Patterson, Bray, & Lee, 2013). Other researchers, however, have suggested that having control over KR enhances learning because it allows the learner to maximize the informational value (i.e., usefulness) of the KR received for the development of error-detection and correction capabilities (e.g., Carter & Patterson, 2012; Chiviakowsky & Wulf, 2002, 2005). At the outset of this dissertation, I acknowledged that increases in motivation may well play a role in self-controlled KR learning advantages, but that I aligned with the notion that the abovementioned information-based processes have a more critical role as many findings exist (e.g., Barros, Tran, Aisner, & Salvadora, 2015; Hansen, Pfeiffer, & Patterson, 2011; Patterson & Lee, 2010) that are difficult to reconcile from the motivation-based explanation. The goal of this dissertation was, therefore, to elaborate on these information-based mechanisms to gain a better understanding of self-controlled KR learning advantages.

Chapter 2 of this dissertation, which was a replication and extension of a previous experiment (Chiviakowsky & Wulf, 2005), investigated the impact of the when the KR decision was made, either before, after, or both before and after a response on motor learning, KR strategies, and the development of error-detection capabilities. The results supported the notion that the KR decision should be made after a motor response to facilitate skill retention and transfer as well as accurate error-detection capabilities. Thus, in all subsequent experiments the KR decision was always made after a

motor response. Based on the findings in Chapter 2, it was hypothesized that essential processing activities must be engaged during the KR-delay interval (i.e., the time period immediately following a response and the KR decision prompt). The experiment reported in Chapter 4 introduced an interpolated activity during the KR-delay interval to investigate whether the learning advantages of self-controlled KR schedules could be eliminated, presumably by interfering and/or blocking the processing of task-intrinsic feedback for error estimation processes that are engaged immediately after a motor response (Swinnen, 1990; Swinnen, Nicholson, Schmidt, & Shapiro, 1990). The results revealed the KR-delay interval as an important time period as the interpolated activity abolished the learning advantages of self-controlled KR schedules. The experiment in Chapter 5 investigated whether self-controlled KR learning advantages could be enhanced using neurostimulation. Specifically, anodal-tDCS was applied over M1 to determine if self-controlled KR learning benefits could in part be attributed to activity in M1. The results suggested that M1 may not significantly contribute to self-controlled KR learning advantages; however, in contrast to Chapters 2 and 4 the learning benefits of self-controlled KR were nominal at best in Chapter 5.

6.1. On the origin of self-controlled KR learning benefits: An information-processing account

One of the earliest explanations for the learning benefits of self-controlled KR schedules relative to yoked schedules was forwarded by Chiviacowsky and Wulf (2002), who proposed that self-controlled KR schedules enhance learning because they are more congruent with the needs of the performer as KR can be requested when it is actually needed/wanted. In contrast, KR was argued to be provided in a random fashion to participants in yoked KR groups. Support for this “congruent with needs hypothesis” was found in their KR questionnaire data wherein most participants in the self-controlled KR group revealed a strategic preference for requesting KR mostly after perceived good trials. When the yoked participants were asked about the KR schedule they experienced, the majority of participants reported

that they felt like they did not receive KR when they would have wanted/needed it. Since their 2002 study, other researchers have also found a self-reported preference of requesting KR mostly after perceived good trials during practice (e.g., Chiviacowsky & Wulf, 2002; Laughlin et al., 2015; Patterson & Carter, 2010; Patterson, Carter, & Hansen, 2013); however, others have reported mixed preferences for requesting KR based on the age of the learner (Carter & Patterson, 2012), the proportion (50% vs. 100%) of self-control trials (Patterson, Carter, & Sanli, 2011), and whether participants are in the early or late stages of practice (Carter & Patterson, 2012; Chapter 3). Interestingly, whenever yoked participants have been queried about their KR schedule, the majority of these participants always report that they felt like KR was not provided when they would have actually wanted it (e.g., Carter & Patterson, 2012; Fairbrother, Laughlin, & Nguyen, 2012; Patterson & Carter, 2010; Patterson et al., 2011), which is consistent with Chiviacowsky and Wulf (2002). Thus, what should be apparent is that unlike participants in yoked groups, participants in self-controlled KR groups can engage in deliberate and purposeful KR strategies that are performance-dependent.

This performance-dependent nature of strategically requesting KR that was found in Chiviacowsky and Wulf's (2002) earlier experiment led to a follow-up study that more closely explored their "congruent with needs hypothesis". In this study, Chiviacowsky and Wulf (2005) manipulated the temporal placement of the KR decision relative to motor execution such that one self-controlled group completed their decision before a trial, whereas the other self-controlled group completed the decision after a trial. Superior transfer performance was found in the group that made their decision after a trial, while the two groups did not differ significantly in retention. Chiviacowsky and Wulf (2005) suggested that transfer tests may be a more sensitive measure of learning and therefore, concluded a learning advantage of making the KR decision after a trial because the learner can base this decision on a comparison between an estimation of their response success and their reference of correctness (see also Hansen et al., 2011; Patterson & Carter, 2010). As discussed in Carter, Carlsen, and Ste-Marie

(2014), we did not agree with the notion that transfer tests are a more sensitive measure of learning; instead, we highlighted that retention and transfer tests provide different, yet complementary information regarding the learning characteristics of permanence and adaptability, respectively. Based on this, a decision to conduct a replication and extension experiment of Chiviawsky and Wulf's (2005) experiment was made to more firmly establish that making the KR decision after a trial is in fact more effective for learning as indicated in both retention and transfer.

The results of Chapter 2 suggest that the learning benefits of self-controlled KR schedules for both retention (i.e., permanence) and transfer (i.e., adaptability) do in fact depend on the option of making the KR decision after a trial. Additional support for this view was provided by the error estimation data in retention and transfer, as well as the open-ended questions regarding KR strategies. Specifically, the two self-controlled groups that had the option to make their KR decision after a trial were significantly more accurate at estimating their performance in retention and transfer when KR was removed compared to their respective yoked groups, as well as the self-controlled group that made their decision before a trial, which did not differ significantly from their yoked counterparts on any behavioural measure in retention and transfer. Moreover, during the inductive thematic analysis it was recognized that completing the KR decision before a motor response precludes participants from being able to request KR based on an estimation of one's performance on a given trial. In retrospect, this inherent difference in strategy affordance would not prevent these participants from requesting KR in a way that was "congruent with their needs". For example, a participant in the Self-Before group described their KR strategy as "I tried back to back feedback, but preferred more spaced out feedback" which seems to highlight this participant's awareness of the strategy that was most congruent with their needs. Thus, it would seem that the "congruent with needs hypothesis" cannot entirely account for why the timing of the KR decision modulates self-controlled KR learning benefits as decisions made before and after a response can be congruent with one's needs.

To resolve this, we (Carter et al., 2014) suggested that having the option to request KR after a motor response allows the learner to request KR only when a comparison between perceived and actual error would maximize the informational value of the KR received; thus reducing uncertainty because information would be transmitted (Guadagnoli & Lee, 2004; Marteniuk, 1976). Such a view combines ideas related to the “usefulness” of the KR (e.g., Chiviacowsky & Wulf, 2005; Hansen et al., 2011) with the notion of information transmission from communication theory (Shannon & Weaver, 1949). Some support for this idea can also be found in the KR strategy response of a Self-Before participant, who stated “Had I been able to change my answer, I would have foregone feedback when I knew I had a bad shot”. This response seems to suggest that when KR is requested for a trial before knowing the outcome of the response, it is possible that KR will be received on trials where its delivery is redundant with response-produced feedback (Archer, Kent, & Mote, 1956; Buekers, Magill, & Hall, 1992; Kernodle, Johnson, & Arnold, 2001; Magill, Chamberlin, & Hall, 1991) as that described in the above example. In other words, a KR request is essentially wasted in these situations as no information is transmitted because there is no uncertainty to be reduced between the participant’s estimation of performance and their reference of correctness.

This “usefulness of KR hypothesis” based on its informational value was appealing as it could not only account for the typical self-controlled KR learning advantage over yoked KR, but also why these advantages were modulated by the temporal placement of the KR decision in Chapter 2. Thus, one obvious prediction of this hypothesis is that any manipulation that effectively reduces to informational value of KR would concomitantly reduce the effectiveness of a self-controlled KR schedule. In fact, Barros et al. (2015) have recently supported this using a balance-task where KR was made to be redundant with task-intrinsic feedback. Interestingly, the results revealed that reducing the usefulness of the KR eliminated the typical learning benefits of self-controlled KR schedules over yoked KR schedules. Another prediction of this “usefulness of KR hypothesis” would be that the KR-delay interval might be a

critical period for these processing activities, which could be tested experimentally using an already established protocol in the motor learning literature, that of interpolated activities (Lee & Magill, 1983, 1987; Marteniuk, 1986; Salmoni, Schmidt, & Walter, 1984; Swinnen, 1990). The underlying assumption in Experiment 2 was that structural interference results from similar high-level processing activities involved in both the interpolated activity and with the normal processing of response-produced feedback upon movement completion; thus, the interpolated activity should diminish self-controlled KR learning advantages based on this “usefulness of KR hypothesis” (Carter et al., 2014).

The results revealed that the interpolated activity not only eliminated the typical self-controlled KR learning advantages, but also resulted in significantly worse retention and transfer performance compared to the traditional self-controlled KR group (i.e., no interpolated activity). At the theoretical level, the findings of Chapter 4 strongly suggest that the KR-delay interval is the hub for processing activities that allow the learner to request KR only when a comparison between perceived and actual error would maximize the informational value of the KR received (Chapter 2). In hindsight, a limitation of Chapter 4 would be not including an assessment of error estimation abilities in retention and transfer as in Chapter 2. The inclusion of measures of error estimation in future self-controlled KR experiments is therefore encouraged to determine whether the greater accuracy on these tests involving simple motor tasks would generalize to more complex tasks. Additionally, future studies could also include estimation trials throughout practice to gain insight into the time course of the development of these error-detection capabilities that have been suggested to be concurrently strengthened with a self-controlled KR schedule (Carter & Patterson, 2012).

6.2. On the brain regions contributing to self-controlled KR learning advantages

It is well established in the motor domain that providing control over KR scheduling to the learner is an effective KR manipulation for both retention and transfer (see Sanli et al., 2013 for a

review). What remains unknown in this area is what brain regions contribute to the learning advantages of self-controlled KR schedules compared to yoked schedules. This issue was explored in Chapter 5 of this dissertation, where it was hypothesized that M1 may be a candidate brain region based on past research demonstrating that M1 is critically involved in the formation and retention of memory representations of acquired motor skills (e.g., Hadipour-Niktarash, Lee, Desmond, & Shadmehr, 2007; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Lin et al., 2009; Lin, Winstein, Fisher, & Wu, 2010; Muellbacher et al., 2002). To this end, anodal-tDCS was applied over M1 which has previously been shown to augment motor learning (e.g., Cuypers et al., 2013; Kantak, Mummidisetty, & Stinear, 2012; Karok & Witney, 2013; Marquez, Zhang, Swinnen, Meesen, & Wenderoth, 2013; Nitsche et al., 2003; Reis & Fritsch, 2011; Reis et al., 2009; Stagg et al., 2011). The results of Chapter 5 did not show a significant effect of tDCS on performance or learning. Moreover, in comparison to Chapters 2 and 4 a weakness of Chapter 5 is that the learning benefits of self-controlled KR schedules were only replicated in single dependent variable (i.e., timing error) and only in transfer. Thus, a self-controlled KR schedule, independent of tDCS, afforded no significant learning advantage over a yoked schedule for spatial and temporal accuracy in retention and for spatial accuracy in transfer. The lack of a strong effect for self-controlled KR in Chapter 5 is peculiar considering the task goals for the waveform-matching task were identical to those used in Chapter 4 during practice, retention, and transfer. The only difference was that the number of practice trials was increased from 60 to 80 trials between the two experiments, which was done to accommodate a specific stimulation duration (18 mins) that fell in between those used successfully in previous research (15 to 20 mins). Thus, when the findings of Chapter 5 are considered as a whole, any conclusions regarding the contributions of M1 to self-controlled learning advantages are rather problematic due to a lack of a significant tDCS effect and more importantly, an inability to strongly replicate self-controlled KR learning advantages in retention and transfer. A more effective approach for future studies interested in identifying the brain regions that are essential,

beneficial, or unnecessary for self-controlled KR learning advantages may be functional magnetic resonance imaging or transcranial magnetic stimulation; however, both these techniques carry a much larger financial burden than tDCS which may affect the feasibility of these (more effective) approaches.

6.3. Concluding remarks

This dissertation adds to our understanding of why self-controlled KR schedules enhance learning relative to yoked schedules; in particular, the information-processing activities that are engaged during practice with respect to the KR decision. Chapter 2 failed to show a positive additive effect of assumed motivational and informational influences (e.g., Chiviacowsky & Wulf, 2005) when participants were permitted to make a KR decision both before and after a trial. Instead, the results revealed that the key factor determining motor learning was the option of completing the KR decision after a trial. It was concluded that this finding further supported the notion that informational factors associated with the processing of task-intrinsic feedback as well as KR for the development of one's error detection and correction mechanism have a greater relative contribution to self-controlled KR learning benefits than any motivational influences associated with exercising choice.

Additional support for a more critical role of information-based processes was found in Chapter 4 where an attention-demanding activity interposed during the KR-delay interval was able to eliminate the typical learning advantages resulting from self-controlled KR schedules. Importantly, the retention and transfer performance of the traditional self-controlled group was significantly more accurate than the self-controlled group with the interpolated activity. Furthermore, no significant differences were found between the two yoked groups which led to the conclusion that the interpolated activity did not simply make learning worse, but instead interfered with processing activities specific to the KR-delay interval in self-controlled KR conditions that are critical for the typically found learning advantages.

In conclusion, the findings of this dissertation generally support a critical role of error detection and correction processes in explaining self-controlled KR learning advantages and thus, add to the growing evidence that suggests our understanding of self-controlled learning advantages should be reconceptualized using a more dominant information-processing perspective rather than a dominant motivation-based perspective, as recommended by Sanli et al. (2013).

6.4. References

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7. Appendices

7.1. Appendix A: Self-controlled KR experiments

Authors	Task	Design	Dependent variable(s)	Practice	Delayed Retention	Delayed Transfer
Chen et al. (2002)	5-digit key-sequence	Cued ^a -Self vs Uncued-Self vs 2 Yoked groups ^a The cue was a prompt screen asking if the learner wanted KR	1. ACE 2. VE	No effect of Self	Learning effect of Self Cued-Self less ACE than Uncued-Self	N/A
Chiviacowsky & Wulf (2002)	4-digit key-sequence	Self vs Yoked	1. AE relative timing 2. AE absolute timing	No effect of Self	No effect of Self	Self less absolute timing error than Yoked
Chiviacowsky & Wulf (2005)	4-digit key-sequence	Self-Before ^a vs Self-After ^a ^a Before and After refer to temporal placement of KR decision relative to task performance <i>*Limitation of no Yoked groups</i>	1. Overall timing error 2. AE relative timing 3. AE absolute timing	No differences	No differences	Self-After less overall and relative timing error scores than Self-Before
Chiviacowsky et al. (2008a)	Beanbag toss	Self vs Yoked	1. Points system	No effect of Self	Learning effect of Self	N/A
Chiviacowsky et al. (2008b)	Beanbag toss	Self only with post hoc group creation based on More (39%; Range was 25-77%) and Less (8%; Range was 2-13%) KR requests	1. Points system	No differences	Self-More higher scores than Self-Less	N/A

Huet et al. (2009)	Walking through virtual doors	Self-Gauge ^a vs Self-Ghost ^b vs Yoked (to Self-Gauge) vs Control (No-KR)	1. Success rate (%)	Effect of Self only with Gauge KR	Effect of Self only with Gauge KR	N/A
		^a Gauge KR was provided with a vertical indicator ^b Ghost KR was provided by superimposing doors on the virtual doors				
Patterson & Carter (2010)	Multiple (3 in total) 5-digit key-sequence	Self vs Yoked	1. %ACE 2. CV	No effect of Self	Learning effect of Self on %ACE and CV	Learning effect of Self on %ACE
Patterson et al. (2011)	5-digit key-sequence	Self-Self ^a vs All-Self ^b vs Faded-Self ^c vs 3 Yoked groups	1. ACE 2. VE	No effect of Self	Learning effect of Self on ACE and VE	Learning effect of Self on ACE
		^a Had choice during 1 st and 2 nd half of practice ^b Had 100% KR in 1 st half then choice in 2 nd half ^c Had Faded KR in 1 st half then choice in 2 nd half			No differences between the 3 Self groups on ACE or VE	No differences between the 3 Self groups on ACE
Hansen et al. (2011)	6-digit key-sequence	Self vs Yoked vs Yoked with Self ^a	1. ACE 2. CE 3. VE 4. # of errors	No effect of Self	No effect of Self on ACE, CE, or VE	Self less ACE than Yoked
		^a Yoked to the absolute number of KR requests of the Self group but not relative placement			Yoked with Self made fewer errors than Self and Yoked	Yoked with Self less VE than Self Yoked with Self fewer errors than Yoked

Carter & Patterson (2012)	Dynamic linear slide task (akin to a force production task)	Self-Young vs Self-Old vs 2 Yoked groups	1. ACE 2. CE 3. VE 4. AD (error estimation: only in retention)	No effect of Self	Learning effect of Self only in Younger adults on AE, VE, and AD	N/A
Chiviacowsky et al. (2012)	Anticipation-timing task	Self vs Self-4 ^a vs Self-30 ^b ^a Were informed an error of 4 ms or less was considered "good" performance ^b Were informed error of 30 ms or less was considered "good" performance <i>*Limitations of no Yoked groups</i>	1. ACE 2. CE 3. VE 4. Perceived competence 5. Self-efficacy 6. Intrinsic motivation	No effect of Self on ACE, CE, or VE Self-30 higher perceived competence than Self-4 but not Self No differences between Self and Self-30, but both higher self-efficacy than Self-4 Self-30 higher motivation scores than Self and Self-4, who were not different from each other	Self and Self-30 less ACE, CE, and VE than Self-4	Self and Self-30 less ACE and VE than Self-4
Fairbrother et al. (2012)	Beanbag toss	Self-Active vs Self-Sedentary vs 2 Yoked groups	1. Points system	No effect of Self	No effect of Self	Learning effect of Self
Ali et al. (2012)	Anticipation-timing task; 3 different speeds	Self-Random vs Self-Blocked vs 2 Yoked groups	1. AE 2. VE	No effect of Self	N/A	Learning effect of Self on AE and VE
Patterson et al. (2013)	Multiple (3 in total) 5-digit key-sequence	Self-Random vs Self-Blocked vs 2 Yoked groups	1. %ACE 2. CV	No effect of Self	Learning effect of Self only with a Random schedule on %ACE	Learning effect of Self on %ACE

Chiviakowsky (2014)	Anticipation-timing task	Self vs Yoked <i>*Introduced novel yoking technique to control for perceived competence (i.e., success experiences due to KR after “good” trials)</i>	1. AE	No effect of Self	Learning effect of Self	N/A
Carter et al. (2014)	Dynamic linear slide task (akin to a force production task)	Self-After vs Self-Before vs Self-Both ^a vs 3 Yoked groups ^a This novel group made an initial decision before a trial but could then change or stay with their original choice after a trial	1. AE 2. AD (error estimation: only in retention and transfer)	No effect of Self	Learning effect of Self only for Self-After and Self-Both on AE and AD No difference between Self-After and Self-Both	Learning effect of Self only for Self-After and Self-Both on AE and AD No difference between Self-After and Self-Both
Tsai & Jwo (2015)	Force production	Self vs Yoked vs Limited Self ^a ^a Limited to a max of 50% per block <i>*Limitation that KR frequency between the Self groups was not controlled for. Self was 74% vs Limited Self was 49%</i>	1. AE 2. VE	Limited Self and Yoked less AE than Self	Limited Self less AE than Self and Yoked (who did not differ)	Limited Self less AE than Self and Yoked (who did not differ) Limited Self and Yoked (who did not differ) less VE than Self
Lim et al. (2015)	Taekwondo Poomsae Taegeuk 1st	Self vs Yoked	1. Points	Performance effect of Self	Learning effect of Self	N/A

Grand et al. (2015)	Beanbag toss	Self vs Yoked	1. RE 2. BVE 3. Feedback related negativity (FRN) potential 4. Intrinsic motivation	No effect of Self on RE or BE Effect of Self on FRN amplitude Effect of Self on an averaged* IMI score of 3 subscales (Interest/Enjoyment, Perceived competence, Effort/Importance) but no effect on the individual subscale scores <i>*Problematic to do an average score as each of these subscales measure a different construct</i>	No effect of Self on RE or BVE	Learning effect of Self on RE
Carter & Ste- Marie (2016)	Waveform matching task	Self vs Self with Interpolated ^a activity vs 2 Yoked groups ^a An interpolated activity was performed during the KR-delay interval	1. RMSE	Performance effect of Self	Learning effect of Self only for Self group that did not have the interpolated activity	Learning effect of Self only for Self group that did not have the interpolated activity

7.2. Appendix B: Ethics approval for Chapters 2 through 4

File Number: H12-12-07

Date (mm/dd/yyyy): 05/01/2014



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

University of Ottawa
Office of Research Ethics and Integrity

Ethics Approval Notice Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

<u>First Name</u>	<u>Last Name</u>	<u>Affiliation</u>	<u>Role</u>
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Michael	Carter	Health Sciences / Human Kinetics	Student Researcher

File Number: H12-12-07

Type of Project: PhD Thesis

Title: Cognitive effort and learner-controlled feedback schedules

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
04/22/2014	04/21/2015	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A

7.3. Appendix C: Ethics approval for Chapter 5

File Number: H03-12-03

Date (mm/dd/yyyy): 03/27/2015



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

University of Ottawa
Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

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File Number: H03-12-03

Type of Project: Professor

Title: Investigating How Modulating Cortical Excitability Affects Motor Performance

<u>Renewal Date (mm/dd/yyyy)</u>	<u>Expiry Date (mm/dd/yyyy)</u>	<u>Approval Type</u>
04/05/2015	04/04/2016	Ia

(Ia: Approval, Ib: Approval for initial stage only)