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Examining the impact of error estimation on the effects of self-controlled feedback

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ABSTRACT

Two experiments were conducted that examined the motivational and informational perspectives concerning learning advantages from self-controlled practice. Three groups were tasked with learning a novel skill; self-controlled (SC), yoked traditional (YT), and yoked with error estimation required during the acquisition phase (YE). Results from the delayed learning measures showed the YE group performed better than the SC and YT groups, for Expt. 1. A similar pattern emerged for Expt. 2, albeit, this was not significant. While there were no motivation differences across the groups in either experiment, a strong correlation in Expt. 2 was shown between error estimation capabilities, which were best for the YE group, and learning. These combined results suggest that informational processes contribute more to the self-controlled feedback learning advantage, relative to motivational contributions.

1. Introduction

Motor skill acquisition can be enhanced by allowing learners to control aspects of their learning environment (for reviews, see Sanli, Patterson, Bray, and Lee (2013) and Wulf (2007)). Most attempts to explain the underlying mechanisms of such benefits have relied on research in which learners were allowed to control their feedback, typically knowledge of results (KR) schedules (e.g., Carter & Ste-Marie, 2017a; Grand et al., 2015; Carter, Carlsen, & Ste-Marie, 2014; Chiviacowsky, de Medeiros, Kaefer, Wally, & Wulf, 2008; Chiviacowsky & Wulf, 2005, 2002). The explanations for the benefits of self-controlled practice environments could be conceptualized as being from two perspectives. One explanation focuses on the relationship between self-controlled feedback and psychological factors. It has been argued that allowing learners to decide when to receive feedback fulfills the learner's psychological need for autonomy (Brydges, Carnahan, Rose, & Dubrowski, 2010; Brydges, Carnahan, Safir, & Dubrowski, 2009; Hartman, 2007; Wulf & Toole, 1999), increases the learner's feelings of self-efficacy (Andrieux, Danna, & Thon, 2012; Bund & Wiemeyer, 2004), and increases learner's task motivation (Chiviacowsky & Wulf, 2002; Chiviacowsky, de Medeiros, et al., 2008) ultimately leading to enhanced motor skill acquisition.

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Although this psychological perspective has received considerable attention in the self-controlled learning literature (e.g., Wulf & Lewthwaite, 2016), an alternative explanation, that has a more cognitive or information processing focus, has also been proposed. Researchers have suggested that self-controlled practice leads to greater engagement in cognitive processes that, in turn, enhance the acquisition of motor skills. Specifically, it has been argued that self-controlled practice conditions lead to deeper information processing (Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995; Wulf, Raupach, & Pfeiffer, 2005), enhanced ability to identify performance errors (Carter & Ste-Marie, 2017a; Carter et al., 2014; Chiviacowsky & Wulf, 2005), increased preparation time (Post, Fairbrother, Barros, & Kulpa, 2014), increased feedback processing (Grand et al., 2015), and increased task recall (Post, Aiken, Laughlin, & Fairbrother, 2016; Post, Fairbrother, & Barros, 2011), which contribute to superior learning. Most of these studies, however, discuss the role of such cognitive processes *a posteriori* with a few notable exceptions that have directly tested the cognitive explanation.

Chiviacowsky and Wulf (2005) investigated whether the benefits of self-controlled feedback were associated with the choice itself or with the timing of that choice. Two self-controlled feedback groups were compared; labeled as self-before and self-after groups. In the self-before group, participants were asked to decide if they wanted feedback before the trial was initiated. In the self-after group, participants were asked to decide if they wanted feedback after the trial was completed. Although there were no differences between groups on acquisition or on a 24 h retention test, the self-after group performed better on a 24 h transfer test. The authors argued that participants in the self-after group were likely involved in error estimation activities with the goal of determining whether the KR would provide useful information, while participants in the self-before were not as likely to engage in such cognitive activities. Based on this, it was suggested that the error estimation processes inherent to self-controlled feedback schedules, rather than the act of choosing itself, contributed to the learning advantages of self-controlled feedback.

Noteworthy, however, is that Chiviacowsky and Wulf (2005) did not include yoked feedback groups, nor were there measures of participants' error estimation abilities, which limits the discussion around the benefits of self-controlled feedback and the suggestion that error estimation was indeed critical. Carter et al. (2014) addressed these limitations by including yoked feedback groups and measures of error estimation during retention and transfer. Additionally, a group in which participants were asked to decide prior to a trial whether KR would be desired, but allowed them to change their minds after the trial (self-both), was included. This self-both group was included from the premise that deciding to receive feedback both before and after a trial might engage both the motivational (before) and cognitive (after) advantages, leading to additive benefits for this group. Carter et al. (2014) results corroborated Chiviacowsky and Wulf (2005) findings; the self-after group performed better than the self-before group. In addition, the self-before group performed similarly to both the yoked feedback groups, suggesting no learning advantages associated with choice before a trial occurred. Moreover, the self-after and self-both groups performed similarly, further suggesting that choice before a trial contributed negligibly to learning benefits. The assumption here is that it was the decision made 'after' the trial that resulted in the self-both group's similar performance to the self-after group, with the decision 'before' the trial not contributing to learning benefits. Finally, the self-after and self-both groups also outperformed all other groups in error estimation in both retention and transfer. Taken together, the results reinforce the role of error estimation in the benefits associated with self-controlled practice.

Working from the logic presented by Chiviacowsky and Wulf (2005) and Carter et al. (2014), Carter and Ste-Marie (2017a) recently investigated if blocking the timeframe in which error estimation activities presumably occur would eliminate the benefits of self-controlled feedback. Specifically, the authors interposed the KR-delay interval with a secondary task that has been shown to disrupt error estimation activities in previous studies (e.g., Marteniuk, 1976; Swinnen, Nicholson, Schmidt, & Shapiro, 1990). The authors compared two self-controlled feedback groups (self-control with interpolated activity and self-control without interpolated activity) and their respective yoked conditions (yoked with interpolated activity and yoked without interpolated activity). The results indicated that participants who had control over their feedback schedule, but were prevented from engaging in error estimation, performed worse than those participants who had control over their feedback schedule but were not required to perform an interpolated task, presumably being free to engage in performance assessment. Furthermore, the self-controlled feedback with interpolated activity performed similarly to the yoked with and without interpolated activity groups. These results thus provided evidence that the cognitive processing occurring after the skill is performed, but before extrinsic feedback is provided (i.e., during the KR-delay interval), which presumably includes performance assessment, were critical to explaining the benefits of self-controlled feedback schedules.

As proposed by others (Carter & Ste-Marie, 2017a; Carter et al., 2014; Chiviacowsky & Wulf, 2005), if indeed these error estimation processes occurring in the KR-delay interval are essential to the learning advantages associated with self-controlled feedback, then it is reasonable to expect that participants who are encouraged to engage in similar processes (i.e. error estimation), without the provision of choice, might not show significant learning differences from a self-controlled group. Alternatively, if the act of choosing is critical because participants' need for autonomy must be met in order to have increased self-efficacy and task motivation, learners in yoked feedback conditions would continue to perform worse than participants in self-controlled feedback conditions, regardless of whether or not they were engaging in performance assessment. Therefore, two experiments were conducted with the purpose of investigating the effects of self-controlled, yoked, and yoked with performance estimation feedback schedules on the acquisition of motor skills.

2. Experiment 1

2.1. Methods

2.1.1. Participants and experimental groups

Sixty college-aged volunteers free from musculoskeletal injuries or sensory-motor/cognitive impairments participated in the experiment. Sample size was not determined by a formal *a priori* power analysis, but was determined based on Lohse, Buchanan, and Miller (2016) who noted that most motor learning experiments are underpowered showing that a selected group of experiments had a median n/group = 11. Therefore, we selected a n/group = 20. Participants were recruited through word of mouth at a large public university in southern California, USA. Participants had limited experience with the experimental task and were naïve to the purpose of the research. Participants were quasi-randomly assigned to one of three experimental groups: self-controlled feedback (SC) (M_{age} = 23.00, SD_{age} = 2.34 years; 11 women, 9 men; 4 left-, 16 right-hand dominant), traditional yoked feedback (YT) (M_{age} = 22.60, SD_{age} = 2.04 years; 11 women, 9 men; 4 left-, 16 right-hand dominant), and yoked feedback with performance estimation (YE) (M_{age} = 22.45, SD_{age} = 1.70 years; 11 women, 9 men; 4 left-, 16 right-hand dominant). The quasi-random assignment involved collecting a bank of self-control participants (e.g., 10) first and then randomly assigning participants to a group while allowing the yoked groups to be matched in terms of handedness and sex. Handedness was determined by asking participants with which hand they would like to perform a throw. All procedures were approved by the university's Institutional Review Board.

2.1.2. Task and materials

The task required participants to perform an underhand throw to a target with their non-dominant hand while blindfolded. The blindfold consisted of opaque ski goggles. Previous literature has demonstrated advantages of self-controlled feedback in the acquisition of this type of task (Chiviacowsky, de Medeiros, et al., 2008; Chiviacowsky, Wulf, de Medeiros, Kaefer, & Tani, 2008). Participants were asked to throw a beanbag weighing approximately 100 g to a circular target positioned flat on the floor. The bullseye had a 10-centimeter radius and the center of the target was positioned three meters away from participants. Nine concentric circles with radii of 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm surrounded the target to measure the accuracy of each of the throws (Fig. 1). Points were awarded based on the final position of the beanbag. If the beanbag landed in the center of the target, 100 points were awarded. If it landed in one of the other target zones 90, 80, 70, 60, 50, 40, 30, 20, or 10 points respectively were awarded based on the distance from the target. If the throw landed outside the largest circle zero points were awarded. In cases in which the beanbag landed on a line, the higher score was awarded.

Participants also completed a questionnaire, designed to measure participants' perceived competence and feeling of autonomy. Specifically, participants completed the perceived competence subscale that was taken directly from the Intrinsic Motivation Inventory (IMI) (McAuley, Duncan, & Tammen, 1989), and a modified version of the perceived choice subscale, termed an autonomy subscale. The perceived choice subscale was not taken directly from the IMI because that subscale is phrased around choice over the task and/or activity, which was not provided to the participants in this experiment. Instead, we modified the perceived choice subscale to reflect the choice available within the practice session. This modified perceived autonomy subscale was similar to the one used in Carter and Ste-Marie (2017b). The perceived competence subscale contained six statements, whereas the perceived autonomy subscale included five statements.

2.1.3. Procedures

This experiment consisted of two phases held on two consecutive days: 1) acquisition and 2) retention/transfer testing. Participants completed data collection individually in a secluded room. Two experimenters were present during data collection. Upon arriving, participants provided written consent and provided information about age, handedness, and physical activity background. The participant was then positioned at the throw line, marked by a foot-long piece of blue masking tape on the floor, and the experimental task was explained. To check for understanding, participants were asked to explain the task and procedures back to the lead experimenter before beginning the protocol.

For the acquisition phase, which lasted approximately 45 min, participants performed six blocks of ten trials while blindfolded. Participants removed the blindfold between blocks. The inter-block interval lasted 90 s. Once ready to start a block of trials, participants were blindfolded and the experimenter would place one beanbag in the participant's non-dominant hand. An experimenter

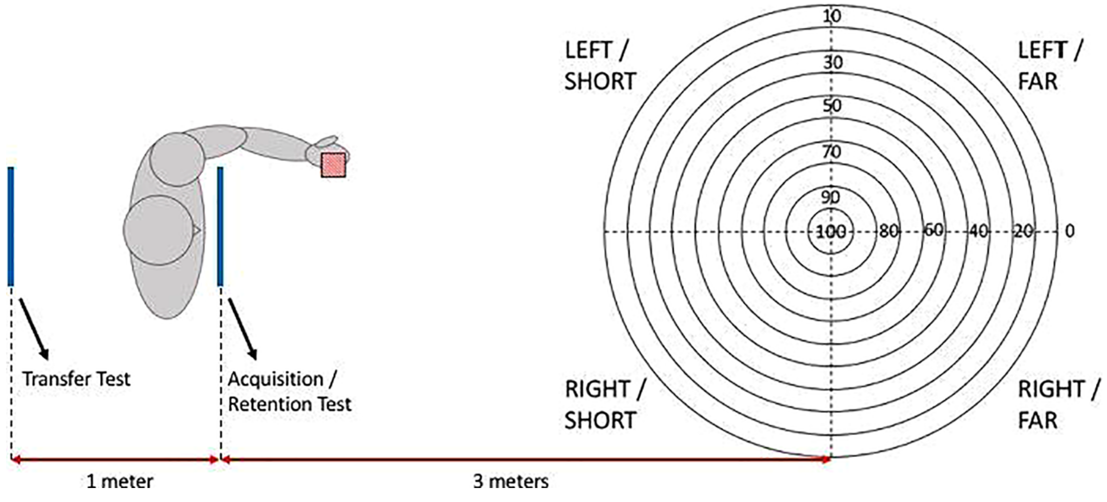

Fig. 1. A schematic representation of the data collection setup for Experiment 1.

would remove the beanbag from the target after each throw after the score was recorded. The experimenter would then place another beanbag in the participant's non-dominant hand for the next trial. At the end of the first and last block of trials, participants in all groups were asked to complete the questionnaire measuring perceived competence and feeling of autonomy by indicating their level of agreement with 11 statements. Prior to the completion of the questionnaire, participants were provided instructions to read all statements and to respond on a 7-point Likert scale based on how true the statement reflected their perceptions (1 = not true at all and 7 = very true).

Participants in the SC group were instructed to ask for KR on 3 of the 10 trials in a block. KR was provided in terms of the number of points scored and the direction of the throw. An example of the feedback provided would be "Your throw landed on 70 points, to the right and far". If the throw landed right in the center of the target participants were told "100 points" and no information about direction. They were also told that if they did not ask for feedback in the first 7 trials of a block, feedback would be provided in the last 3 trials on that block. No participants opted to receive all of their feedback in the last 3 trials of the block. Participants were also told that the following day, when their performance would be tested, feedback would not be provided.

Participants in the YT and YE groups were matched in sex and handedness to participants in the SC group. These participants received feedback in the schedule chosen by their SC counterparts. They were told that sometimes they would receive feedback but sometimes they would not. Participants were also told that the following day, when their performance would be tested, feedback would not be provided. The participants in the YE group were additionally asked to estimate their performance. The point estimation performed by YE participants followed the same format as the KR provided by the experimenter. Specifically, participants were asked to estimate the number of points (0–100) and direction of the throw (short/far; left/right) immediately after every trial and before receiving feedback. An example of an error estimation response by a participant in the YE group would be "70, to the left and short".

Approximately 24 h after the acquisition phase, the retention/transfer testing phase was conducted. This phase lasted approximately 20 min. The retention test consisted of 10 trials, performed at the same distance from the center of the target, during which participants were again prevented from seeing the target area while performing an underhand toss to a target with their non-dominant hand. No feedback was provided during retention testing. Immediately following the retention test, participants completed a transfer test. For the transfer test, participants performed the same task but were positioned four meters away from the center of the target. Feedback was also not provided during the transfer test. Participants were allowed to remove the blindfold between retention and transfer test and look at the target from the starting line for the transfer test.

2.1.4. Statistical analyses

Visual inspection of the data suggested some extreme values, possibly caused by shifts in a participant's feet while blindfolded. To eliminate these outlier trials, we used the median absolute deviation (MAD) procedure as described in Leys, Ley, Klein, Bernard, and Licata (2013). Leys et al. argued that removing outliers from data sets using mean and standard deviation tends to assume normality of data that include outliers, is highly influenced by the outlying data points themselves, and is highly ineffective in identifying outliers in small data sets, such as those typical in motor learning research. In contrast, the MAD procedure is less sensitive to outliers in the data set and less influenced by the sample size. In this experiment, values that were greater than or smaller than the median by more than three times the MAD were removed, an approach considered very conservative (Leys et al., 2013). One "round" of the MAD procedure was conducted resulting in the removal of 4.61% of trials in acquisition, 4.67% of trials in retention, and 6.67% of trials in transfer.

After outlier trials were removed, the dependent variables were calculated. The primary dependent variables used were: 1) mean points, calculated by averaging the points obtained in each ten trial block; 2) mean autonomy scores, calculated by averaging the points obtained for each of the autonomy-related statements (statements 2, 4, 6, 8, and 10); 3) mean competence scores, calculated by averaging the points obtained for each of the competence-related statements (statements 1, 3, 5, 7, 9, and 11); and 4) mean point estimation error, calculated for the YE group by averaging the absolute difference between points obtained and point estimation for each trial in a block of ten trials.

Our analyses involved all three experimental groups using procedures described below. When the sphericity assumption was violated the Greenhouse-Geisser corrected values are reported and partial eta-squared (η^2_{partial}) is reported as an estimate of effect size. Bonferroni post hoc analyses were used when appropriate. In all cases, alpha was set at 0.05.

2.2. Results

2.2.1. Acquisition

Fig. 2 (left side) illustrates mean points for all groups in the acquisition, which were analyzed in a 3 (Group: SC, YT, YE) × 6 (Block) mixed-model ANOVA with repeated measures on Block. All groups improved their performance across acquisition blocks, which was supported by a significant main effect for Block, $F(3.72, 212.06) = 5.79$, $p < .001$, $\eta^2_{\text{partial}} = 0.09$. Post hoc (Bonferroni) analysis indicated mean points in block 1 differed from blocks 5 ($p = .018$) and 6 ($p = .001$), while mean points in block 2 differed from block 6 ($p = .003$). The main effect of Group, $F(2, 57) = 0.19$, $p = .828$ $\eta^2_{\text{partial}} = 0.01$, and the Group × Block interaction, $F(7.44, 212.06) = 0.53$, $p = .869$, $\eta^2_{\text{partial}} = 0.02$, were not significant.

2.2.2. Retention and transfer

Potential retention and transfer performance differences were assessed via a 3 (Group: SC, YT, YE) × 2 (Test: Retention, Transfer) ANOVA with repeated measures on Test. In retention (Fig. 2, middle), the YE group scored the most points, followed by the SC group, then the YT group. A similar pattern of findings was observed in transfer (Fig. 2, right) as the YE group scored the most points, the YT

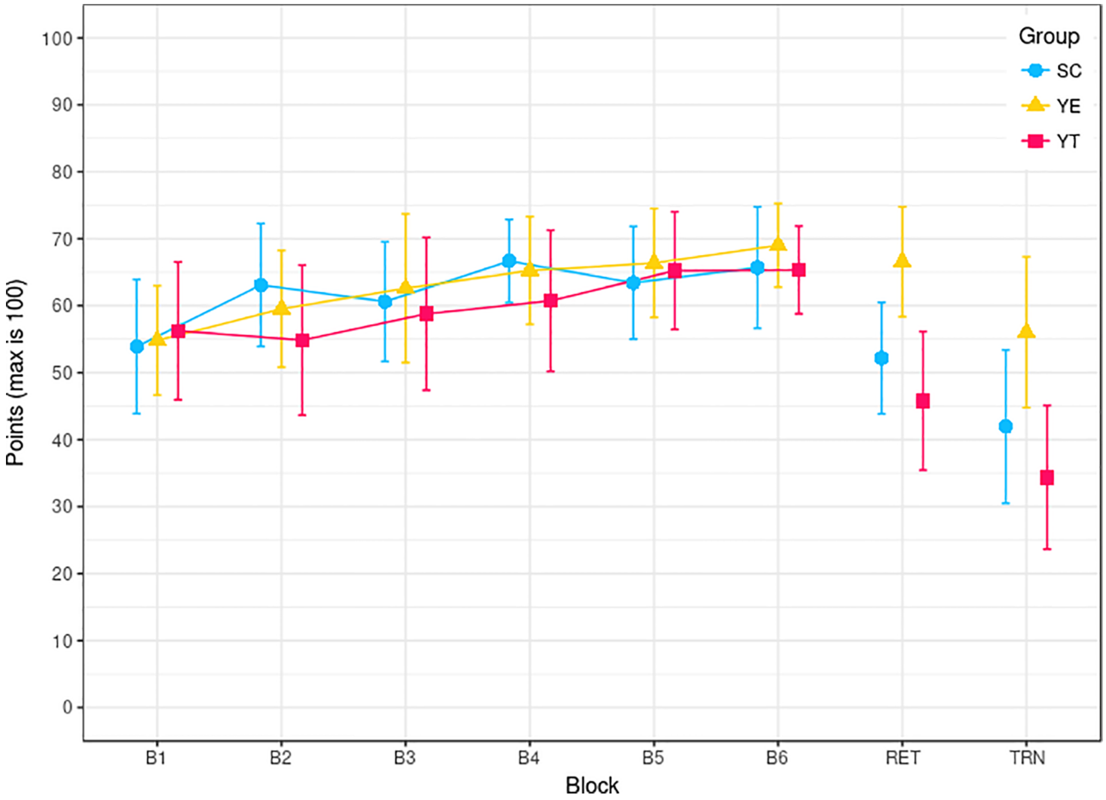

Fig. 2. Mean points (with 95% confidence intervals) scored during the acquisition (B1-B6), retention (RET), and transfer (TRN) phases of the experiment for the self-controlled (SC, blue circles), the traditional yoked (YT, red squares), and the yoked with estimation (YE, yellow triangles) groups. Please refer to online version for references to color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

group scored the least points, and the SC group was in the middle. The main effect for Group was significant, $F(2, 57) = 7.54$, $p = .001$, $\eta^2_{\text{partial}} = 0.21$, and Bonferroni post hoc procedures indicated participants in the YE group scored significantly more points than participants in the SC group ($p = .040$) and the YT group ($p = .001$). However, participants in the SC group were not statistically different from participants in the YT group ($p = .647$). Additionally, there was a significant main effect for Test, $F(1, 57) = 10.84$, $p = .002$, $\eta^2_{\text{partial}} = 0.16$, demonstrating that participants performed better in retention than in transfer. The Group × Test interaction, $F(2, 57) = 0.01$, $p = .988$, $\eta^2_{\text{partial}} = 0.00$, was not significant.

2.2.3. Questionnaire scores

Practice related changes in mean perceived autonomy and competence scores were assessed by separate 3 (Group: SC, YT, YE) × 2 (Time: Block 1 and Block 6) ANOVAs with repeated measures on Time. Self-reported levels of perceived autonomy (Fig. 3, left) were largely unchanged between the two time points across all groups. The analysis revealed that the main effects of Time, $F(1, 57) = 2.63$, $p = .111$, $\eta^2_{\text{partial}} = 0.04$, and Group, $F(2, 57) = 0.90$, $p = .411$, $\eta^2_{\text{partial}} = 0.03$, as well as the Group × Time interaction, $F(2, 57) = 0.01$, $p = .987$, $\eta^2_{\text{partial}} = 0.04$, failed to reach statistical significance. In contrast, perceived competence (Fig. 3, right) in all groups increased from Block 1 to Block 6, which was supported by a main effect of Time, $F(1, 57) = 23.32$, $p < .001$, $\eta^2_{\text{partial}} = 0.44$. The main effect of Group, $F(2, 57) = 1.79$, $p = .176$, $\eta^2_{\text{partial}} = 0.06$, and the Group × Time interaction, $F(2, 57) = 1.96$, $p = .150$, $\eta^2_{\text{partial}} = 0.06$, were not significant.

2.2.4. Performance estimation

A repeated measures ANOVA was used to compare mean performance estimation error across acquisition blocks for the YE group. Participants in the YE group became more accurate at estimating their earned points across acquisition blocks. A significant main effect for Block, $F(5, 95) = 7.36$, $p < .001$, $\eta^2_{\text{partial}} = 0.28$, was found, with the post hoc analysis showing that performance estimation was less accurate in block 1 (M = 27.35, SE = 2.18) compared to blocks 5 ($p = .001$; M = 18.15, SE = 2.01) and 6 ($p < .001$; M = 17.15, SE = 1.50). Performance estimation in blocks 2 (M = 23.50, SE = 2.43) and 3 (M = 24.90, SE = 2.83) was less accurate than in blocks 5 ($p = .008$ and 0.011, respectively) and 6 ($p = .004$ and 0.001). Lastly, performance estimation in block 4 (M = 22.10, SE = 2.57) was less accurate than block 6 ($p = .011$).

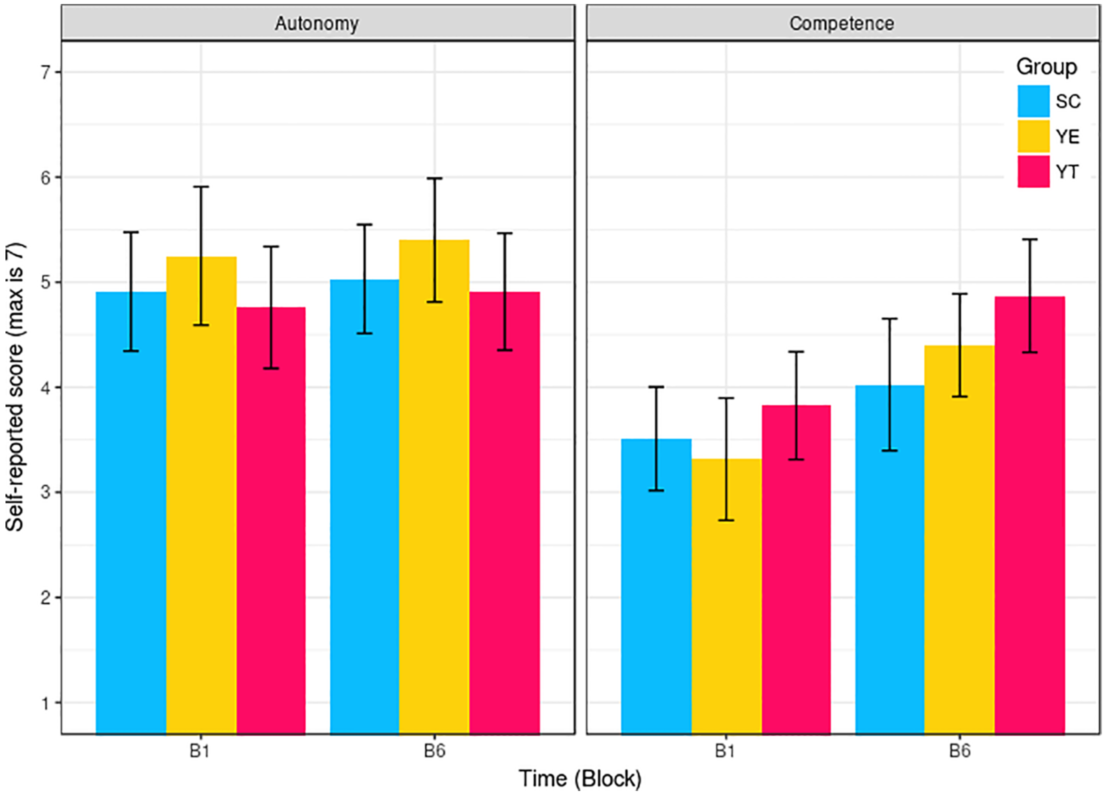

Fig. 3. Mean scores (with 95% confidence intervals) for perceived competence and perceived autonomy for the SC group (left, blue bar in each set of both panels), the YE group (middle, yellow bar in each set of both panels), and the YT group (right, red bar in each set of both panels) groups. Questionnaires were administered after Blocks 1 (B1) and 6 (B6) of the practice phase. There were no significant group differences for either perceived competence or perceived autonomy. Perceived competence scores, however, increased significantly from Block 1 to Block 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Discussion

The purpose of Experiment 1 was to further understand the role of performance estimation on the effects of self-controlled feedback. Specifically, we investigated if participants receiving yoked feedback schedules, but also asked to engage in performance estimation, would demonstrate similar performance to that of participants in a self-controlled group or traditional yoked group. The results clearly indicated that the yoked performance estimation group outperformed the yoked traditional group in retention and transfer, suggesting that explicitly engaging yoked participants in performance estimation leads to enhanced skill acquisition. This is in line with previous research highlighting the importance of error estimation processes to the acquisition of motor skills (e.g., Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997). The SC group, however, was inferior in performance during retention and transfer to the YE group. Moreover, we did not obtain the standard advantages associated with self-controlled feedback as the SC group did not show superior performance over the YT group. Combined, the lack of these significant differences, limits our capacity to interpret the results of the role of performance estimation on the effects of self-controlled feedback, and we further elaborate on these points next. To begin, the absence of significant self-controlled feedback benefits was unexpected given previous studies (e.g., Chiviacowsky, Wulf, et al., 2008) have demonstrated beneficial effects of self-controlled feedback using the same throwing task. Our failure to replicate the standard self-controlled benefit might be related to these previous studies (e.g., Chiviacowsky, de Medeiros, et al., 2008, Chiviacowsky, Wulf, et al., 2008) using 10-year old children, who likely have less throwing experience and thus more room for improvement and performance differences than the university aged students used in our experiment. As pointed out by Lohse et al. (2016), the ability to replicate results found in previous studies is fundamental for the development of the field of motor learning. While it is not entirely obvious why the effects were not observed in the current experiment, it is possible that there were subtle differences in protocol (e.g., exact instructions, difference in age of participants) and/or analyses (e.g., outlier procedures, tests for assumptions) which may have contributed to our failure to replicate. Indeed, Lohse et al. pointed out that the description of such procedures is fundamental for reproducibility, theory testing, and knowledge generation in the area of motor learning.

Also of influence is that the YE group performed better than the self-controlled learning group in retention and transfer. While it has been speculated that participants in a SC group *spontaneously* engage in performance/error estimation when making their feedback decisions (e.g., Carter et al., 2014; Chiviacowsky & Wulf, 2005), it is possible that, in this experiment, participants in the YE group became more attuned to using their intrinsic feedback by explicitly asking them to estimate their performance after each practice trial. This would prove advantageous in retention and transfer when KR is removed and participants must rely on their own intrinsic feedback to assess and modify performance from trial to trial. Indeed, the YE group's retention and transfer performance was significantly more accurate than the traditional yoked group—a group that has been suggested to thwart the development of independent error detection and correction abilities (e.g., Carter et al., 2014; Carter & Ste-Marie, 2017a). Thus, our results do suggest that the typical negative impact on learning from practicing in a yoked group can be remedied through error estimation, which is in line with other research demonstrating that training the cognitive processes necessary to assess one's performance contributes to the acquisition of motor skills (e.g., Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997). However, whether enhanced error estimation was in fact present during retention and transfer remains unknown as estimations were not assessed on these learning tests.

Lastly, our questionnaire measures of perceived competence and perceived autonomy both revealed no significant differences between groups. While this finding is consistent with recent work (e.g., Carter & Ste-Marie, 2017b; Grand et al., 2015), it is inconsistent with predictions from the motivational perspective (e.g., Wulf & Lewthwaite, 2016). Specifically, it would be expected that being able to exercise choice (i.e., self-controlled group) would positively impact (i.e., increase) perceptions of autonomy and competence, and in turn enhance motor learning. Neither of which was noted in the current experiment. We do, however, acknowledge this argument is weakened by our failure to replicate the usual self-controlled learning advantage. Although it is possible these psychological constructs were negatively impacted by restricting the amount of self-controlled trials, we feel this is unlikely given past research has shown that having fewer self-controlled opportunities can be as (e.g., Patterson, Carter, & Sanli, 2011) or more (e.g., Hansen, Pfeiffer, & Patterson, 2011) effective than unlimited opportunities. Additionally, past research has used a similar technique of restricting feedback requests to 3 trials within a 10-trial block and found the usual self-controlled learning advantage (e.g., Carter et al., 2014; Carter & Ste-Marie, 2017a; Chiviacowsky & Wulf, 2005). We chose to conduct a second experiment to address some of the limitations of Expt. 1 to continue our investigation into the role of error estimation in the learning advantages of self-controlled feedback schedules.

3. Experiment 2

In Experiment 2, our main goal was to continue examining the impact of engaging in performance estimation processes by a group who does not have choice over feedback in comparison to a learning group who does have choice, but to address the noted limitations of Experiment 1. To begin, we sought to address the limitation of having the YE group engaged in overt error estimation on every trial, and thus, had the yoked group only explicitly provide error estimation on the same schedule as that in which the SC feedback group requested KR. We believed this protocol to more accurately align with the SC feedback group, which were free to engage (or not) in error estimation after every trial, but in which we assumed that error-estimation had occurred when feedback was in fact requested. As such, the yoked performance estimation group was asked to estimate their performance only on trials in which they would receive KR, which was yoked to the schedule of a counterpart in the self-controlled group. Further, performance estimation capabilities were measured during the retention and transfer phases and were presumed to provide an index of participants' capabilities to evaluate their movement outcome in relation to the movement time goal.

In order to potentially increase learners' perception of autonomy, we also modified the experimental protocol such that participants in the self-controlled feedback group were able to choose when to receive feedback with less restriction. That is, rather than indicating that they had to request feedback three times within a block of 10 trials, they were simply told that they would receive 20 feedback trials and could choose when to receive those at any point during acquisition with the constraint of having to use all 20 requests. Additionally, we chose to change the task to be learned. In Experiment 1, the average performance between SC and YK groups, despite not being significantly different, appeared to match previous literature. Perhaps the dependent variable used was not sensitive enough to accurately reflect these differences (for discussions see Fischman, 2015; Hancock, Butler, & Fischman, 1995; Reeve, Fischman, Christina, & Cauraugh, 1994). Therefore, we selected a laboratory task that has shown self-controlled feedback learning benefits (e.g., Carter & Ste-Marie, 2017a, 2017b). We believed this task change would be advantageous because it would allow for a more precise measure of performance. Further, a meta-analysis (McKay, Carter, & Ste-Marie, 2014) revealed that self-controlled learning advantages have been found for both laboratory-based and applied tasks, and thus the use of a laboratory-based task is not problematic. A final change is that we also added items related to the subscale of interest/enjoyment from the IMI (McAuley et al., 1989) within the questionnaire items used to capture perceptions of autonomy and competence because it is considered the scale most tightly linked to intrinsic motivation.

Similar to Experiment 1, the performance of the yoked group with performance estimation is pivotal in relation to the self-controlled and yoked traditional groups. The proposal is that if we see the usual self-controlled learning benefits, we can then compare to which group the yoked performance estimation group aligns. The autonomy supportive perspective would lead to the prediction that a similar performance should be seen as that of the yoked traditional group because of the lack of choice, whereas the information-processing perspective leads to the prediction that the engagement in performance estimation would have this group perform better than the yoked traditional group, and more similar to the self-controlled group. Contrasting predictions can also be made for correlation analyses between both the motivational (i.e., IMI subscales) and informational (error estimation accuracy) measures and that of the dependent measure of absolute constant error of movement time. Specifically, if there are stronger motivational contributions for physical performance of the task, then a stronger correlation should occur between these two variables than that found between the informational measure and physical performance of the task. In turn, the opposite would occur should there be greater informational contributions; i.e., a stronger correlation will be seen between error estimation accuracy and absolute constant error of movement time.

3.1. Method

3.1.1. Participants and experimental groups

Sixty right-handed participants who self-reported no sensory or motor dysfunctions completed the experiment. Consistent with Experiment 1, sample size was not determined by a formal a priori power calculation but was based on suggestions made by Lohse et al. (2016). Handedness was confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were recruited by word of mouth and provided informed written consent prior to the start of the experiment. All participants had no experience with the experimental task, self-controlled procedures, and were naive to the purpose of the research. Participants were quasi-randomly assigned to one of three equal size experimental groups: the self-control group (SC) (M_{age} = 21.05, SD_{age} = 1.73 years; 10 women, 10 men), the yoked traditional group (YT) (M_{age} = 21.6, SD_{age} = 2.19 years; 15 women, 5 men), or the yoked performance estimation group (YE) (M_{age} = 21.3, SD_{age} = 2.18 years; 11 women, 9 men). The quasi-random assignment was similar to Experiment 1 with a bank of self-control participants (e.g. 5) being collected first and then randomly assigning participants to one of the two remaining groups afterwards. Thus, the difference was that yoked participants did not have to be matched in terms of sex and handedness because all participants were right-hand dominant. The experimental procedure was approved by the Research Ethics Board of a major university in Ontario, Canada.

3.1.2. Task and materials

Participants performed two rapid extension-flexion reversal movements with their non-dominant (left) arm in order to reproduce a goal waveform as accurately as possible (as seen in Fig. 4). The waveform was a summation of two sine waves: $y(t) = 42\sin(\pi t - 0.3) + 23\sin(3\pi t + 0.4)$. For this waveform matching task, the movement time goal was 900 ms for the practice and retention phases. The transfer phase had the waveform stretched along the x-axis (i.e., the same amplitude goals), which resulted in a movement time increase to 1150 ms. This waveform matching task has been widely used in the motor learning literature (e.g., Goh, Sullivan, Gordon, Wulf, & Winstein, 2012; Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010; Leinen, Shea, & Panzer, 2015); thus, the procedures are well-established. After participants completed the written consent form, they sat facing a 22-in. computer monitor with their left arm resting in a padded armrest of a custom manipulandum. The participant's elbow was positioned directly over the center of rotation of the manipulandum, which was affixed to a nearly frictionless vertical axle that limited movement to the horizontal plane. Participants' grasped a handle that had been adjusted according to their limb length. Vision of their arm was blocked using a felt sheet. The home position during this task had the participant's elbow bent at approximately 90 degrees with their arm directly in front of their abdomen. The home position was indicated by a padded L-bracket, which the participants rested the manipulandum against at the start and end of every trial. Position data on each trial was provided using a linear potentiometer powered by a 5 V direct current power supply attached to central axis of the manipulandum. Movements were sampled at 1 kHz for the duration of each trial using analog-to-digital hardware (National Instruments Inc. PCIe-6321). A custom LabVIEW (National Instruments Inc.) program controlled the timing of the experimental protocol, recorded, and saved the data for offline analysis.

Consistent with Experiment 1, participants completed a questionnaire during the acquisition phase that included the perceived competence subscale taken from the IMI and a modified perceived autonomy subscale. Additionally, we included the task interest and enjoyment subscale of the IMI (McAuley et al., 1989). The task interest/enjoyment subscale was added to this experiment because it is argued to be the subscale that best captures intrinsic motivation. The task interest/enjoyment subscale contained seven statements, whereas the perceived competence and modified perceived autonomy subscales consisted of six and four statements, respectively.

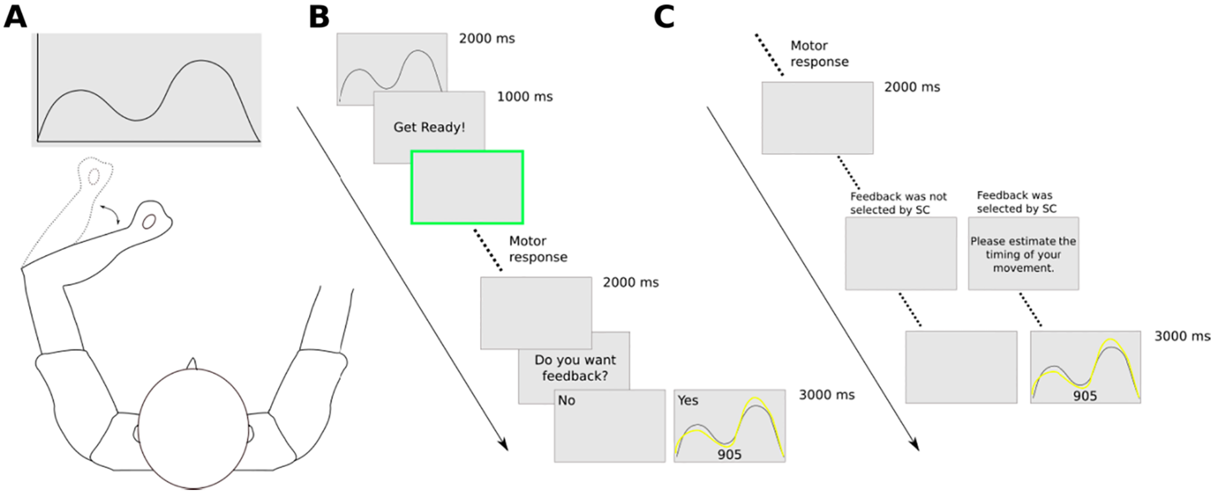

Fig. 4. (A) Schematic representation of the goal waveform, which involved participants completing two extension-flexion reversals. (B) An outline of the sequence of events that a self-control participant viewed on the computer monitor during the acquisition phase. The only difference for the yoked traditional group was the fact that a no feedback prompt was provided. The feedback prompt was also not displayed during the retention and transfer phases of the experiment. (C) The sequence of events that the yoked estimation group viewed on the computer monitor, which was the same sequence that was provided to the self-control and yoked traditional groups until after the motor response.

3.1.3. Procedures

After participants were seated and placed in the correct position, the experimenter read a series of instructions to them that were simultaneously presented on the monitor in front of the participant. The instructions described the task goal and its movement time, how KR would be scheduled based on their experimental group, how KR would be displayed, and how to properly interpret the KR display. All participants were informed that the acquisition phase would consist of six blocks of ten trials (60 total trials) with KR occurring on 20 trials. Thus, a relative KR frequency of 33.3% was provided to all participants.

The SC participants were informed that they had to decide if they wanted to receive feedback at the conclusion of each trial, with the constraints of only receiving KR on 20 trials, and that all 20 requests had to be used. The two yoked groups were instructed that they would receive feedback on 20 trials out of the 60 trials according to a predetermined schedule. This yoking procedure was completed in order to ensure that any learning differences were due to the provision of choice instead of the relative frequency of the KR. Further, the yoked performance estimation group (YE) was informed that they would receive a prompt prior to the receipt of KR, asking them to estimate their movement time (ms). Therefore, they were instructed that they would complete this performance estimation task on the 20 trials in which they received KR feedback.

As indicated in Fig. 4, at the beginning of each trial, the target waveform was displayed on the computer screen for 2000 ms, followed by a “Get Ready!” and a visual “GO” signal (1000 ms apart). However, as this was not a reaction time task, participants were instructed to begin the trial when ready, following the “GO” signal. For the purposes of this experiment, movement time was defined as the onset of movement (leave home position) to the completion of movement (return to the home position) as measured by the linear potentiometer. During the ongoing movement, the computer monitor remained blank. Upon completion of the movement, a 2000 ms KR-delay interval occurred that consisted of a blank screen for all groups. Following this delay, the KR prompt was given to the self-control group whereas the YE group received the prompt to estimate their movement time if KR was being provided on that trial. When KR was provided, it was displayed for 3000 ms and consisted of a graphic representation of the participant’s movement trajectory superimposed on the goal waveform, as well as the participant’s movement time (ms). On no-KR trials, a blank screen was displayed for 3000 ms.

Participants completed the questionnaire after blocks one and six during the acquisition phase, identical to that used in Experiment 1. Participants then returned approximately 24 h after the acquisition phase to complete the retention and transfer testing phase. Learning was inferred from performance during this phase. Both of these tests consisted of one block of 10 no-KR trials. To test the hypothesis that an enhanced ability to detect and correct errors may be part of the learning advantage of self-controlled KR schedules, all participants received a prompt to estimate their movement time (ms) after each trial in retention and transfer.

3.1.4. Statistical analyses

Absolute constant error (ACE) of movement time (MT) was used as the primary dependent variable in order to assess performance differences during acquisition, retention, and transfer. ACE MT was selected as the primary dependent variable for two main reasons with the first being that in this experimental design all participants were provided with explicit MT feedback and when participants were required to estimate their performance, they were asked to estimate their movement time (ms). The second reason ACE MT was selected as the primary dependent variable was that in our previous research we saw that the temporal measure was more sensitive compared to the spatial measure (Carter, Smith, Carlsen, & Ste-Marie, 2017). We therefore assumed it to be the most informative measure regarding performance.[3] ACE indicates the mean amount of bias for a group of participants without regard for the direction of bias, thus it is not susceptible to “canceling” effects across participants (Schmidt & Lee, 2011). If a participant completed an incorrect waveform (i.e., participant moved from the home position before the “Go” signal, or had an incorrect number of reversals) the trials were qualitatively removed from analysis by an experimenter who screened all trials. These incorrect waveform trials were removed from analysis, which resulted in the removal of 8.0%, 6.5%, 5.3% trials from acquisition, retention, and transfer. As in Experiment 1, we used the same conservative MAD outlier procedure (Leys et al., 2013) for ACE of MT for acquisition, retention, and transfer trials. As a consequence of this procedure 4.6%, 2.8% and 3.6% of trials were removed from acquisition, retention, and transfer, respectively.

To index performance estimation accuracy, which is argued to be a key component of self-controlled learning advantages from the information-processing perspective (e.g., Carter et al., 2014; Carter & Ste-Marie, 2017b; Chiviacowsky & Wulf, 2005), we calculated ACE of performance estimation (PE) in retention and transfer. ACE PE was calculated as the absolute of the $\Sigma\,(Xi\text{-}T)/n$, where Xi is the estimated movement time, T is the actual movement time, and n is the number of trials (Schmidt & Lee, 2011). Outlier trials were removed with the MAD procedure, which resulted in the removal of 4.3% of trials in retention and 2.5% in transfer. Lastly, the task interest/enjoyment, perceived competence, and perceived autonomy subscales scores were calculated by the same procedures described in Experiment 1.

While the assumption of normality was violated, Norman (2010) argues that ANOVAs are robust and, with sample sizes larger 10 in a group, this parametric statistic can still be used. Consequently, ANOVAs were used and differences with a probability of < 0.05 were considered significant. The Greenhouse-Geisser correction was used when sphericity was violated and partial eta-squared (η^2_{partial}) is reported as an estimate of effect size. Bonferroni post hoc procedures were conducted for any significant ANOVAs.

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[3] Secondary dependent variables root mean square error and absolute constant error of spatial error (degrees) were also collected and analyzed but all revealed the same non-significant pattern of results as ACE MT.

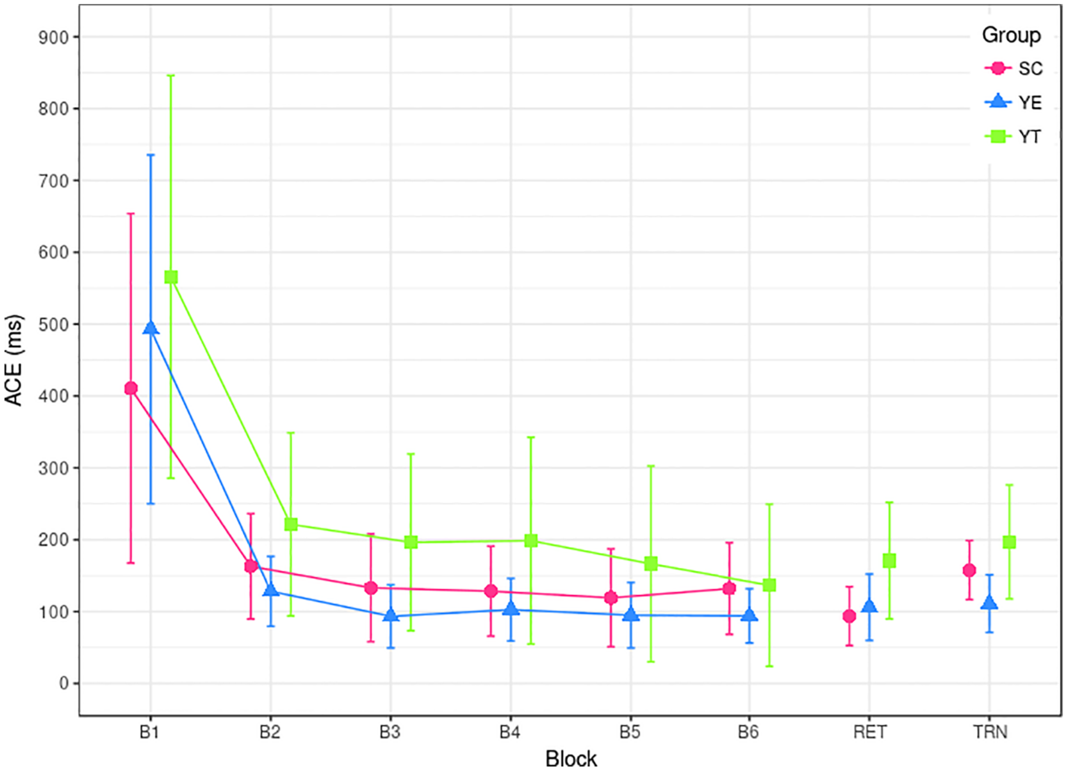

Fig. 5. Mean (with 95% confidence intervals) absolute constant error of movement time (ms) for the acquisition (B1-B6), retention (RET), and transfer (TRN) phases of Experiment 2. Each block consisted of ten trials, and feedback was available only during acquisition. All groups significantly reduced their timing error over practice and importantly, there were no group differences in either Block 1 or Block 6.

3.2. Results

3.2.1. Acquisition

Movement time accuracy in the acquisition phase was analyzed in a 3 (Group: SC, YT, YE) × 6 (Block: 1–6) mixed model ANOVA with repeated measures on Block. Mean ACE of MT decreased across practice blocks for all groups (Fig. 5, left side). There was a significant main effect for Block, $F(1.28, 72.94) = 33.19, p < .001, \eta^2_{\text{partial}} = 0.37$, demonstrating that performance improved across acquisition blocks. Specifically, block 1 performance was significantly more errorful than blocks 2 ($p = < 0.001$), 3 ($p = < 0.001$), 4 ($p = < 0.001$), 5 ($p = < 0.001$), and 6 ($p = < 0.001$) and that block 2 performance was significantly more errorful than block 6 ($p = .030$). Neither the main effect for Group, $F(2, 57) = 0.76, p = .474, \eta^2_{\text{partial}} = 0.03$, nor the Group × Block interaction, $F(2.56, 72.94) = 0.46, p = .680, \eta^2_{\text{partial}} = 0.01$, were significant.

3.2.2. Retention and transfer

Learning differences were assessed via a 3 (Group: SC, YT, YE) × 2 (Test: Retention, Transfer) ANOVA with repeated measures on Test. In retention (Fig. 5, middle), the SC group had numerically less error than the YE group, followed by the YT group. In transfer (Fig. 5, right), it was the YE group who performed with the least error, followed by the SC group, and the YT group having the most error. However, the main effect of Group, $F(2, 57) = 2.74, p = .073, \eta^2_{\text{partial}} = 0.09$, and Test, $F(1, 57) = 3.91, p = .053, \eta^2_{\text{partial}} = 0.06$, as well as the interaction of these two factors, $F(2, 57) = 1.16, p = .322, \eta^2_{\text{partial}} = 0.04$, were not significant.

3.2.3. Questionnaire scores

Self-reported scores, as a function of group, for the three psychological constructs assessed are displayed in Fig. 6. Mean scores for perceived autonomy, competence, and task interest/enjoyment were analyzed using separate 3 (Group: SC, YT, YE) × 2 (Time: Block 1 and Block 6) ANOVAs with repeated measures on Block. For perceived autonomy (Fig. 6, left), the main effect of Time, $F(1, 57) = 2.32, p = .133, \eta^2_{\text{partial}} = 0.04$, and Group, $F(2, 57) = 0.47, p = .627, \eta^2_{\text{partial}} = 0.02$, as well the interaction between these two factors, $F(2, 57) = 0.05, p = .953, \eta^2_{\text{partial}} = 0.002$, all failed to reach statistical significance. Perceived competence (Fig. 6, middle) scores increased from Block 1 to Block 6, which was supported by a significant main effect of Time, $F(1, 57) = 54.21, p < .001, \eta^2_{\text{partial}} = 0.49$. Neither the main effect of Group, $F(2, 57) = 1.02, p = .367, \eta^2_{\text{partial}} = 0.04$, nor the Group × Time interaction, $F(2, 57) = 0.10, p = .909, \eta^2_{\text{partial}} = 0.003$, were significant. Similar to perceived competence, task interest/enjoyment scores (Fig. 6, right) increased from Block 1 to Block 6, which was supported by a significant main effect of Time, $F(1, 57) = 16.84, p < .001, \eta^2_{\text{partial}} = 0.23$. The main effect of Group, $F(2, 57) = 0.97, p = .386, \eta^2_{\text{partial}} = 0.03$, and the Group × Time interaction, $F(2, 57) = 0.68, p = .511, \eta^2_{\text{partial}} = 0.02$, were not significant.

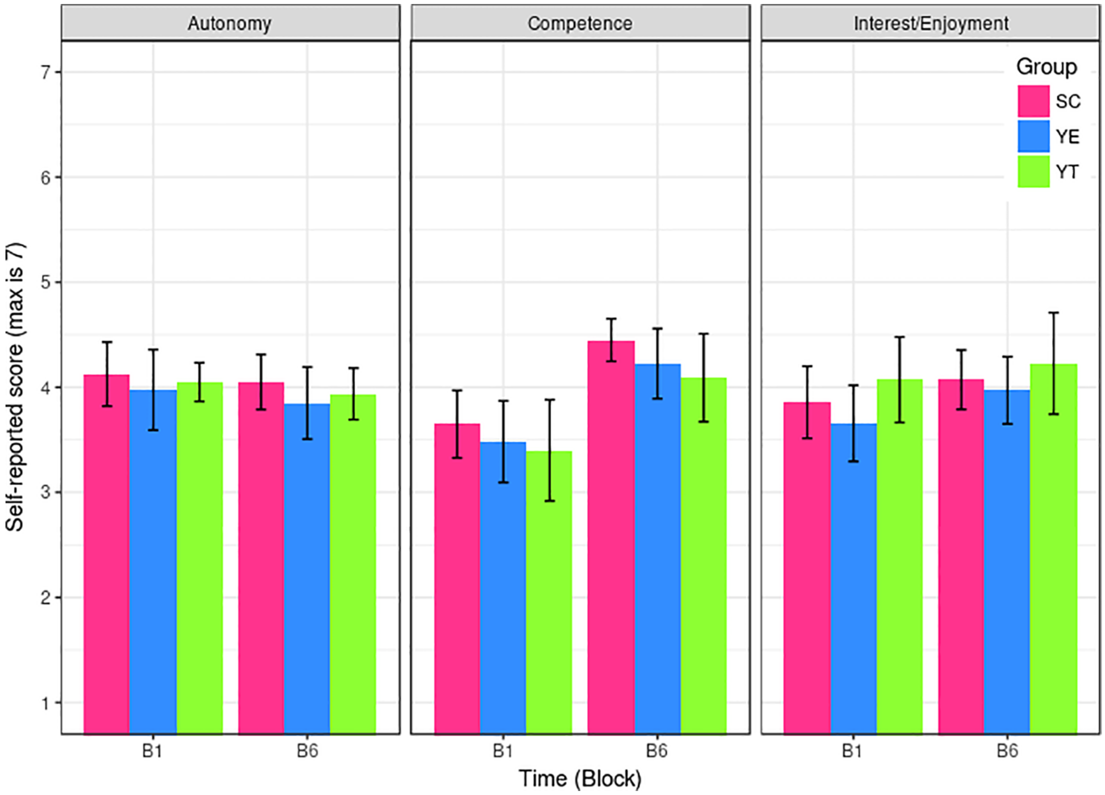

Fig. 6. Mean (with 95% confidence intervals) perceived autonomy, perceived competence, and task interest/enjoyment scores for the SC group (left, red bar in each set in all panels), the YE group (middle, blue bar in each set in all panels), and the YT group (right, green bar in each set in all panels). The questionnaires were administered after Blocks 1 (B1) and 6 (B6) of the practice phase. No significant group differences were found for either psychological construct; however, both perceived competence and task interest/enjoyment scores significantly increased from Block 1 to Block 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.4. Performance estimation

Performance estimation accuracy for all groups in retention and transfer are displayed in Fig. 7, and were analyzed using a 3 (Group: SC, YT, YE) × 2 (Test: Retention, Transfer) mixed ANOVA with repeated measures on Test. As can be seen in Fig. 7, ACE PE was lower in retention compared to transfer, which was supported by significant main effect of Test, $F(1, 57) = 5.58$, $p = .022$, $\eta^2_{\text{partial}} = 0.09$. There was a significant main effect of group, $F(2, 57) = 3.49$, $p = .037$, $\eta^2_{\text{partial}} = 0.11$. Bonferroni post hoc procedures revealed that the YE ($p = .032$, M = 88.69, SE = 13.74) group had significantly more accurate ACE PE compared to the YT (M = 167.01, SE = 23.72) group, but was not different from the SC group ($p = .601$, M = 127.12, SE = 13.57). The SC group was also not different from the YT group ($p = .552$). The interaction between Group and Test was not significant, $F(2, 57) = 0.73$, $p = .489$, $\eta^2_{\text{partial}} = 0.03$.

3.2.5. Correlation of PE to ACE MT

Separate partial correlations were completed for retention and transfer to examine if there was a relationship between performance estimation accuracy and ACE MT with group serving as the covariate. Bias-corrected and accelerated (BCa) bootstrapping procedures were completed to provide 95% confidence intervals (CI; Efron, 1987). ACE MT is plotted as a function of performance estimation accuracy for all groups in Fig. 8 for retention (left) and transfer (right). When we control for group we find a significant relationship between PE and ACE MT for retention, $r = 0.83$, *95% BCa CI* (*0.62*, *0.94*), $p < .001$. Further, there was also a significant relationship between PE and ACE MT during transfer, $r = 0.84$, *95% BCa CI* (*0.74*, *0.91*), $p < .001$.

3.2.6. Correlation of the IMI subscales to ACE MT

Separate partial correlations were completed for the three IMI subscales to examine if there was a relationship between the subscales and physical performance while controlling for group (i.e., ACE MT) for both retention and transfer. The IMI subscales scores after practice (i.e., block 6) were used for the correlation analyses. BCa bootstrapping procedures were completed to provide 95% confidence intervals (Efron, 1987). The correlations between autonomy and ACE MT were not significant for retention, $r = -0.14$, *95% BCa CI* (*−0.30*, *0.01*), $p = .303$, and transfer, $r = -0.12$, *95% BCa CI* (*−0.31*, *0.05*), $p = .366$. Similarly, the correlation for perceived competence and ACE MT also revealed a negative non-significant relationship for both retention, $r = -0.16$, *95% BCa CI* (*−0.50*, *0.26*), $p = .219$ and transfer, $r = -0.11$, *95% BCa CI* (*−0.51*, *0.31*), $p = .415$. Results for the

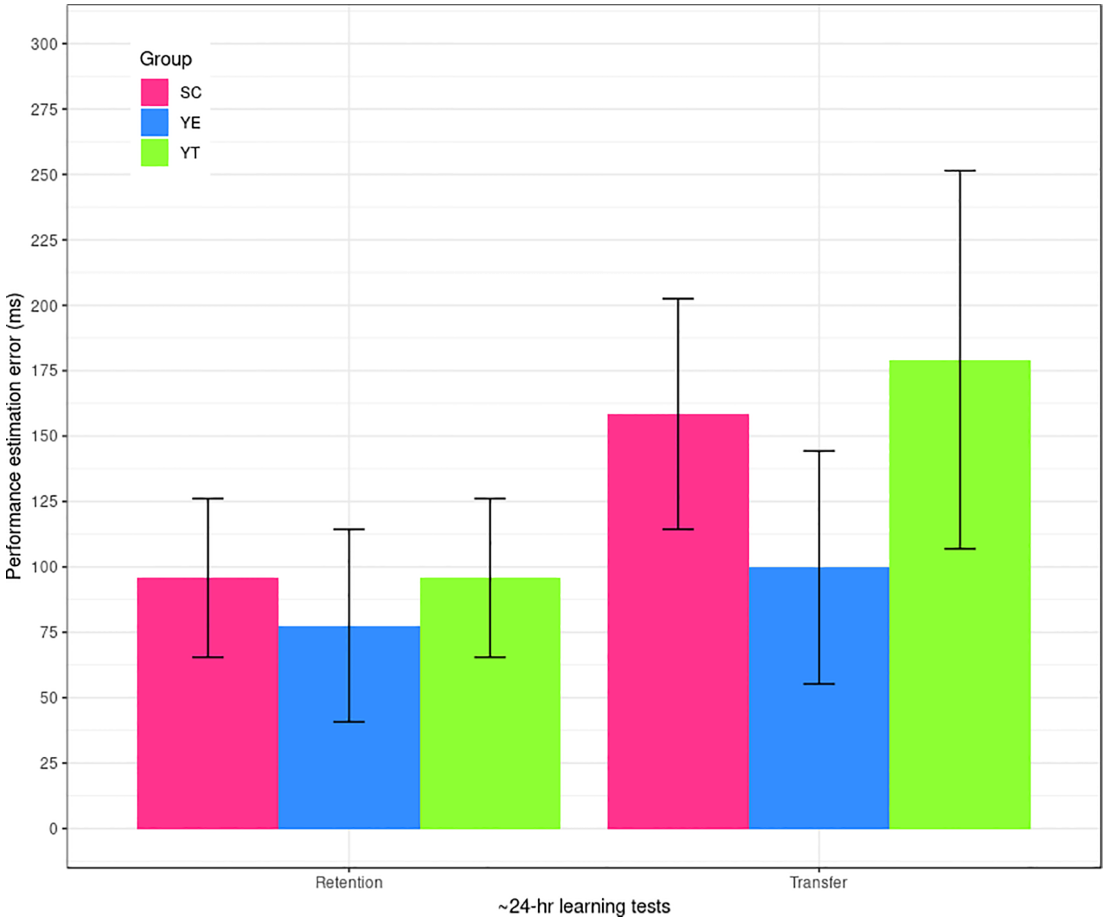

Fig. 7. Mean (with 95% confidence intervals) absolute constant error of performance estimation scores for the SC group (left, red bars), the YE group (middle, blue bars), and the YT group (right, green bars) for the retention and transfer phases of Experiment 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

correlation between intrinsic motivation (i.e., task interest and enjoyment subscale) and retention performance (i.e., ACE MT) revealed a non-significant relationship, $r = 0.01$, *95% BCa CI* (-0.25, 0.27), $p = .949$. Further, there was also a non-significant correlation between intrinsic motivation and ACE MT during transfer, $r = 0.03$, *95% BCa CI* (-0.30, 0.29), $p = .836$.

3.3. Discussion

Here, we continued our examination into the role of error estimation for self-controlled learning advantages while addressing some limitations of Experiment 1. First, instead of restricting feedback to 3 trials in each block of 10 trials, participants were free to schedule 20 feedback trials (33.3%) however they wanted. Second, we included the interest/enjoyment subscale of the IMI as intrinsic motivation is suggested to be a factor determining motor learning from the motivational perspective (Wulf & Lewthwaite, 2016) and it is this subscale that specifically captures intrinsic motivation (Deci, Eghrari, Patrick, & Leone, 1994). Third, we explicitly tested error estimation accuracy in retention and transfer as this has been argued to be a mechanism underlying self-controlled learning advantages (Carter & Ste-Marie, 2017a; Chiviacowsky & Wulf, 2005). Lastly, we switched from a more applied task to a laboratory-based task so performance could be measured more precisely. Importantly, self-controlled learning advantages are found for both applied and laboratory tasks (McKay et al., 2014).

Self-controlled learning advantages were not found—a finding that mirrors Experiment 1 but is inconsistent with the extant self-controlled literature (see Sanli et al. (2013) for a review). Despite this failure to replicate, it is noteworthy that the YE group and the SC group had similar performance outcomes in retention and transfer for both movement time accuracy and error estimation accuracy. Indeed, the ACE PE analysis revealed that the YE group was significantly more accurate than the YT group, suggesting that some of the negative aspects of a yoked schedule could be eliminated by explicitly training participants to use and interpret intrinsic feedback sources. The SC group, unexpectedly however, were not significantly better than the YT group. It is possible that the added requirement to determine whether KR was desired, as compared to the YE group, created informational processing demands that were too demanding and limited this group from fully benefiting from the error-estimation processes. Further research on this notion is recommended.

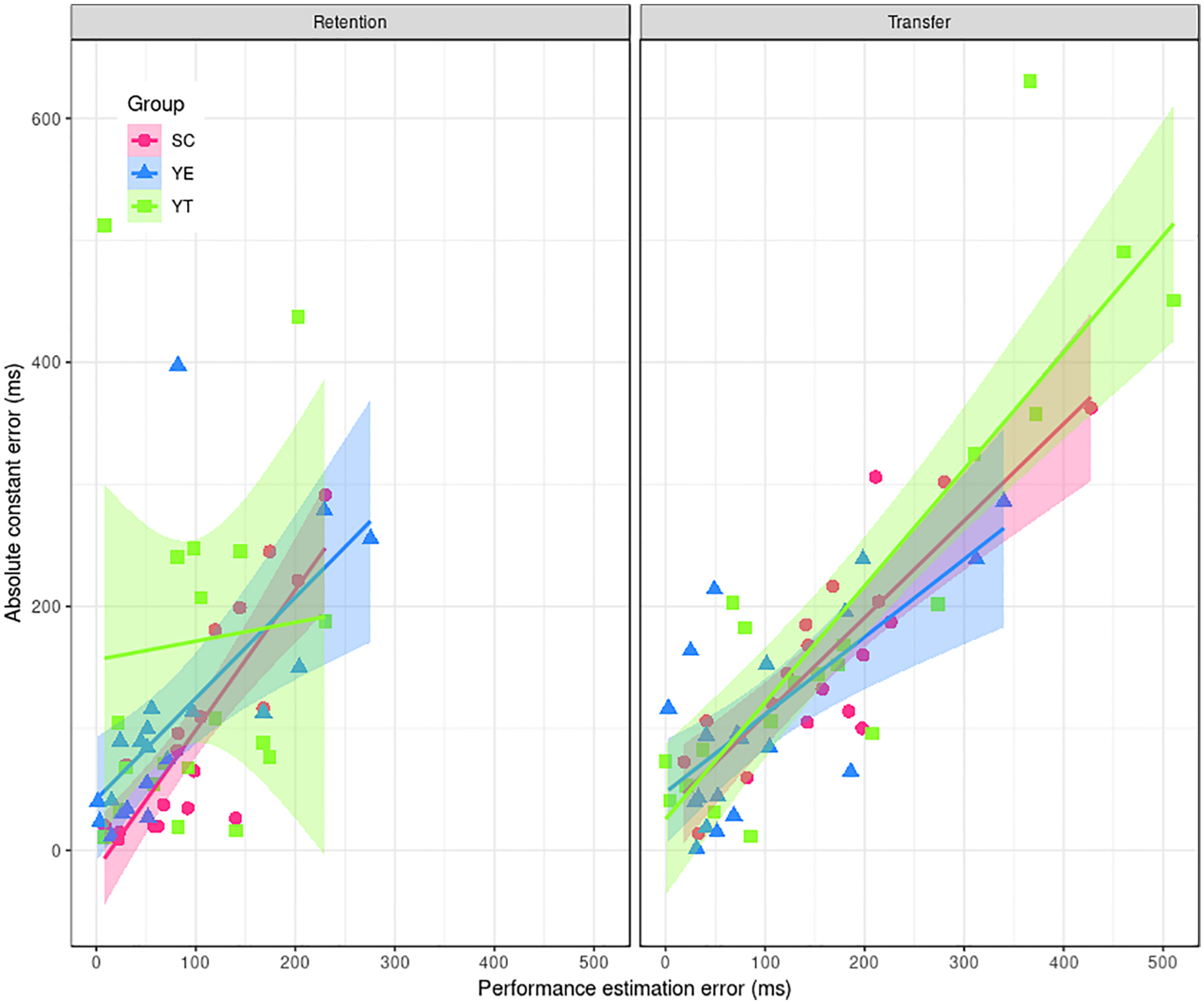

Fig. 8. Scatterplot illustrating the relationship between absolute constant error of performance estimation (ms) and absolute constant error of movement time (ms) for the retention and transfer phases of Experiment 2 (shaded area represents 95% confidence interval). Data of the participants in the SC group are depicted with red circles, in the YT group are depicted with green squares, and in the YE group in blue triangles. There was a strong, positive linear relationship between performance estimation accuracy and physical performance in both retention and transfer tests while controlling for group membership. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The correlation used to examine whether error estimation accuracy had a relationship with physical performance, however, does suggest that error estimation could play an important role in self-controlled learning benefits. The results demonstrated a positive relationship between ACE PE and ACE MT for both the retention and transfer phases; showing that when a learner has more accurate performance estimation they will also have increased physical performance, regardless of their experimental group. In contrast, there were no significant relationships between any of the subscales of the IMI and ACE MT. The findings from these correlation analyses suggest that motor performance during the retention and transfer phases were influenced more by informational, as opposed to motivational, factors.

Despite the self-controlled learning advantage not being replicated, it is still of note that our questionnaire data does not support predictions regarding key psychological constructs from the motivational perspective (Wulf & Lewthwaite, 2016). That is, no group differences were found for either perceived autonomy, perceived competence, or interest/enjoyment. A significant increase in perceived competence and task interest/enjoyment over time (Fig. 6, middle and right sections), however, was found. This latter finding suggests that the questionnaire was sensitive to changes across time in these constructs, and thus, could have possibly been sensitive enough to capture group differences had differences existed. Notable though, is that the motivational measures were collected approximately 24 h prior to the retention test, and thus, no motivational measures were obtained during the retention/transfer phase. The 24-hour interval may have impacted motivation measures differently adding a confounding factor to our partial-correlation analyses. This limitation should be addressed in future research. Nonetheless, the lack of group differences on these measures is consistent with recent self-controlled research (e.g., Carter & Ste-Marie, 2017b; Grand et al., 2015; Grand, Daou, Lohse, & Miller, 2017; Ste-Marie, Vertes, Law, & Rymal, 2013), although others have reported group differences in these (or related) psychological constructs (e.g., Chiviacowsky, 2014; Leiker et al., 2016; Wulf et al., 2017). Further obscuring the potential role of psychological variables in the learning advantages is that Ste-Marie, Carter, Law, Vertes, and Smith (2016) have shown, using a causal modelling technique, that self-efficacy and intrinsic motivation do not explain self-controlled learning advantages. Thus, simply being able to exercise choice may not be sufficient on its own to increase autonomy, competence, and/or intrinsic motivation and such motivational processes may have more of a secondary or modulatory influence on self-controlled learning advantages.

4. General discussion

The benefits of self-controlled over yoked feedback conditions have been extensively described (for a review, see Wulf, 2007); however, there is still uncertainty about the mechanisms underlying that advantage. Some researchers have argued that allowing learners to decide when to receive feedback fulfills the learner's psychological needs (e.g. autonomy), which in turn leads to enhanced motor skill acquisition (Sanli et al., 2013; Wulf & Lewthwaite, 2016). Conversely, others have suggested that self-controlled feedback leads to greater engagement in cognitive processes (e.g. error estimation) that, in turn, enhance the acquisition of motor skills (Carter & Ste-Marie, 2017a; Carter et al., 2014; Chiviacowsky & Wulf, 2005). While these two perspectives present different underlying mechanisms, it is certainly plausible that both of these work in concert. Certainly, findings in which choices that are incidental to the task, such as the choosing the color of a ball (Lewthwaite, Chiviacowsky, & Wulf, 2012) or the mat color to which one throws a lasso (Wulf et al., 2017) suggest that choice can have influences independent of information factors. In the present experiments, we aimed to further understand the role of each of these factors in explaining the benefits of self-control feedback. Understanding the possible varied contributions of the underlying mechanisms associated with self-controlled feedback advantages is important as it informs theory, guides future research, and contributes to the development of pedagogical and clinical tools.

4.1. The role of psychological factors

The motivational explanation states that allowing learners to decide when to receive feedback fulfills the learner's psychological needs, which in turn leads to enhanced motor skill acquisition (Sanli et al., 2013; Wulf & Lewthwaite, 2016). This explanation is primarily grounded in the Self-Determination Theory (Deci et al., 1994; Deci & Ryan, 2000; for a review see Sanli et al., 2013). In summary, characteristics of the environment, such as the ability to choose when to receive feedback, influence learners' basic psychological needs of autonomy, competence and relatedness, increasing learners' self-determined motivation, leading to positive motivational consequences (i.e. behavioral, affective, or cognitive changes), (Katartzi & Vlachopoulos, 2011). Sanli et al. (2013) note that although researchers in the self-controlled literature tend to focus on behavioral consequences (i.e., performance improvement), including measures of cognitive and affective changes might allow for a better understanding of the factors underlying self-controlled manipulation effects.

Here, we included measures of participants' perceptions of autonomy, competence, and task interest/enjoyment (this latter one in Expt 2 only) at the beginning and end of practice. We expected higher perceived autonomy, competence and, subsequently, task interest/enjoyment scores for the self-controlled group over the two yoked groups who were not provided choice, as predicted by the motivational perspective (Wulf & Lewthwaite, 2016). Based on those same predictions we expected groups with higher scores for perceived autonomy, competence, and task interest/enjoyment to also have higher performance scores. Neither of these expectations were met.

For perceived autonomy, our results indicated no differences between groups and no changes with practice, even in Experiment 2 where participants had relatively greater opportunity to exercise their ability to choose. Additionally, although perceived competence and task interest/enjoyment (Experiment 2) scores increased with practice for all groups, no differences between groups were found. These findings are in line with recent self-controlled research (e.g., Carter & Ste-Marie, 2017b; Grand et al., 2015; Grand et al., 2017; Ste-Marie et al., 2013; Ste-Marie et al., 2016) and weaken the argument that allowing learners to determine their own feedback schedules is sufficient to lead to changes in psychological variables that in turn would lead to enhanced motor skill acquisition. The link between such psychological variables and performance is further weakened by the findings of the present experiments because we observed group differences in performance despite the lack of group differences in psychological variables related to the perceptions of autonomy, competence and task interest/enjoyment. We draw specific attention to the fact that the yoked with error estimation group in Experiment 1 performed more accurately than the traditional yoked group. In addition, our analyses in both experiments indicated no correlation between any of the psychological variables at the end of acquisition and performance on retention and transfer tests. Perhaps, then, other factors may play a more prominent role in mediating the relationship between self-controlled feedback and enhanced motor skills.

4.2. The role of error estimation

To understand the possible contributions of error estimation processes to the benefits of self-controlled feedback, we compared the performance of participants receiving feedback under yoked schedules (i.e., groups with no choice) to that of a self-controlled group. While participants in both yoked groups had the KR schedule of a self-controlled counterpart imposed on them, the critical difference is that in both Experiments one yoked group was explicitly instructed to engage in performance estimation processes during practice, whereas the other was given no instruction. We expected participants in the yoked feedback with error estimation groups to demonstrate similar performance to that of participants in self-controlled feedback groups and thus, also outperform participants in traditional yoked feedback groups. We also expected participants in the traditional yoked groups to have poorer error estimation ability than participants in either of the other groups. Our expectations were partially met.

Our results indicated that the participants in the yoked error estimation groups and participants in the self-controlled feedback group had similar performances in retention and transfer tests. However, the typical self-controlled feedback effects were not observed, limiting the interpretation of these results. Nevertheless, error estimation had a positive effect on learning. Specifically, we observed that the yoked error estimation groups performed better than the traditional yoked groups during retention and transfer in Experiment 1. We also noted that the yoked error estimation group (Experiment 2) was also more accurate in error estimation during retention and transfer compared to the traditional yoked group. Therefore, it is likely the development of error estimation abilities led to the enhanced acquisition of motor skills for participants in that group, at least in relation to the traditional yoked feedback groups. The role of error estimation in performance is highlighted by the strong correlation between error estimation accuracy and performance in retention and transfer for all groups. Given the known relationship between error estimation processes and motor skill acquisition (e.g., Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997), when this is considered in conjunction with recent work by Carter and Ste-Marie (2017a), Carter et al. (2014) and Chiviacowsky and Wulf (2005), our results suggest error estimation might contribute to the benefits of self-controlled feedback.

4.3. On the replication of typical self-controlled feedback findings

Although the benefits of self-controlled practice manipulations generally, and self-controlled feedback specifically, have been extensively described (for reviews see Wulf (2007) and Sanli et al. (2013)), our results suggest that perhaps the magnitude of these effects, and potential confounding factors, are still not fully understood. In the present experiments, self-controlled feedback groups performed numerically better in retention and transfer than the traditional yoked feedback groups. However, these differences were not statistically significant. To be noted, is that both experiments showed high levels of variability in the dependent variables and neither experiment included a pre-test, which may have later served as a covariate to potentially control for such individual differences. In future research, it would be wise to control for this limitation of the experimental design. Regardless, this lack of significance occurred in spite of our choice to use tasks and procedures that have previously produced typical self-control benefits. It is important to mention that even though these results are not statistically significant, they still fall in the predicted directions and it is possible that these results are within the sampling variation of the “true” effect-size for self-controlled learning. Further, we also speculate our failure to replicate typical self-control benefits is associated with subtle differences in experimental procedures and/or analyses. Matching procedures and analyses of previous research would be facilitated if detailed descriptions of experimental protocols (e.g. instructions) and analyses (e.g. outlier removal), as suggested by Lohse et al. (2016), were included in previous studies. We also recognize that our method of selecting sample size is a limitation and recommend that researchers base their sample size on formal priori power calculations aligning with the suggestions made by Lohse et al. (2016).

5. Conclusion

In conclusion, the results of these experiments suggest that the beneficial effects of allowing learners to control their feedback schedules are perhaps smaller than previously indicated in the literature. We offer this conclusion based on the fact that here, following recommendation forwarded by Lohse et al. (2016) to increase replication of experiments, we used tasks and procedures previously found in the literature and did not find significant benefits for the self-controlled feedback condition over the traditional yoked condition. Additionally, the low number of publications that fail to identify typical self-controlled feedback benefits—to our knowledge there are only two (Carter & Patterson, 2012; Carter et al., 2017)—suggest a publication bias limiting an adequate discussion of the magnitude and mechanisms that support said benefits.

Finally, given the combined findings that (1) a yoked group who was encouraged to error estimate showed increased performance to that of a traditional yoked group, (2), that performance estimation ability was positively related to motor performance in retention and transfer, while (3) psychological measures of autonomy, competence, or task enjoyment/motivation were not significantly related to motor performance in retention and transfer, and (4) that those who were allowed to choose their feedback schedule did not show greater scores on psychological measures of autonomy, competence, or task enjoyment/motivation than those who were not, it is suggested that the contributions of informational factors to self-controlled feedback advantages are greater than motivational contributions. It is recommended that variables which test predictions relating to error estimation and feedback processing in relation to self-controlled learning advantages should be included in future studies.

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Declarations of interest

None.

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