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Neural mechanism underlying self-controlled feedback on motor skill learning

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ABSTRACT

The present study investigated the neural mechanisms of self-controlled (SC) feedback underlying its learning advantages. Forty-two participants, including 24 females (16.43 ± 2.61 years) and 18 males (17.56 ± 0.86 years), were randomly assigned to a SC or yoked (YK) group. The 6-key-pressing task with a goal movement time was adopted as the experimental task. The behavioral results showed that the SC group demonstrated superior performance in transfer; however, the differences in retention did not reach statistical significance. Event-related potential analyses revealed that the SC group exhibited larger post-stimulus and post-feedback P3 amplitudes than the YK group in the frontal regions; these amplitudes were larger in the YK group in the parietal regions. The post-response error positivity amplitude was found to be larger in the YK group than in the SC group. These results suggest that SC feedback may allow the learner to more actively process the task stimuli and feedback information, and contributes to enhancing the learner's motivation and attachment to the task being practiced. The present study provides a neurophysiological explanation for why SC feedback is effective in learning a new motor skill.

1. Introduction

Since Janelle, Kim, and Singer (1995) proposed a self-controlled (SC) feedback method in the domain of motor learning, the effectiveness of SC feedback has been verified across a variety of motor tasks, including timed key-pressing (Chen, Hendrick, & Lidor, 2002; Chiviacowsky & Wulf, 2002, 2005; Hansen, Pfeiffer, & Patterson, 2011; Patterson, Carter, & Sanli, 2011; Patterson & Lee, 2010), beanbag toss (Chiviacowsky, Wulf, deMedeiros, Kaefer, & Tani, 2008; Chiviacowsky, Wulf, de Medeiros, Kaefer, & Wally, 2008), disk throw (Hodges, Edwards, Luttin, & Bowcock, 2011), golf ball toss (Janelle et al., 1995), tennis ball throw (Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997), and walking through obstacles (Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009). In most of the previous studies, SC subjects outperformed their yoked (YK) counterparts in retention or transfer tests.

Why is it then effective to give learners control over the feedback they receive? Janelle et al. (1995) hypothesized that SC subjects were able to process and retain information more effectively, not relying on feedback. A number of other studies have also suggested that increased, deeper, or more efficient information processing is a possible reason for superior learning in the SC condition relative to the YK condition (Hartman, 2007; Patterson et al., 2011; Post, Fairbrother, & Barros, 2011; Wulf, Clauss, Shea, & Whitacre, 2001). Bund and Wiemeyer (2004) suggested the idea of cognitive effort, stating that self-control created greater strain on cognition by requiring the learner to monitor and evaluate stimuli, correct errors, and make decisions in the process of acquisition. It was speculated that spontaneous error estimations might contribute to the SC learning advantages (Chiviacowsky & Wulf, 2005) and that an optimal amount of cognitive effort could expedite motor learning (Patterson & Lee, 2010). However, the assertion that SC

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feedback facilitates cognitive processing of the learner remains rather speculative, having failed to be grounded in empirical evidence.

Another broadly discussed explanation for the benefit of SC feedback is that SC learners are highly motivated in the process of learning. This theoretical perspective coincides with self-determination approach to motivation (Ryan & Deci, 2007). SC participants are known to experience greater responsibility to reach proficiency, which may heighten their intrinsic motivation to perform well (Janelle et al., 1997). Similarly, Wulf, Raupach, and Pfeiffer (2005) proposed that more active involvement in the learning process might lead to increased motivation. Chen et al. (2002) hypothesized that SC learners understood why they were learning and valued it, and their implicitly enhanced intrinsic motivation associated with self-control benefited their cognitive processes. In contrast, YK subjects may feel control-deprived, and therefore experience less intrinsic motivation and invest less effort (Wulf & Toole, 1999). For YK participants, the absence of feedback when they want it likely makes the practice context less desirable, which may demotivate them (Chiviacowsky & Wulf, 2002). Notably, because the motivational and cognitive explanations are closely inter-connected, they should not be understood separately: increased motivation through active involvement in the task contributes to the cognitive processes of the learner, while increased cognitive efforts during acquisition may enhance motivation by encouraging the learner's sense of challenge (Sanli, Patterson, Bray, & Lee, 2013).

Despite the rationale offered by the previous studies that the effectiveness of SC feedback is attributable to better cognitive processing and heightened motivation of the learner, these studies have not quantified or empirically evaluated the basis for this rationale. Therefore, the mechanism underlying the advantages of SC feedback remains elusive. To understand whether learners process feedback information based on a schedule they choose themselves or on one determined by someone else, it is necessary to examine the functional activities of the brain involved in feedback processing. However, even though the present study was designed to manipulate the practice context for feedback reception, it is known that feedback characteristics not only affect its processing by the learner, but are also closely linked to how the learner processes the task stimulus and response errors (Luft, 2014; Rosch & Hawk, 2013). Therefore, the neural activities throughout the entire learning process need to be investigated, from receiving a task stimulus to initiating a response to receiving feedback.

In a study by Grand et al. (2015), differences in feedback processing and motivation between the SC and YK groups were examined in the process of learning beanbag toss. The authors found that the SC group exhibited higher feedback-related negativity (FRN) amplitude, with higher motivation scores and higher accuracy in transfer tests, suggesting that SC feedback enhances cognitive processing of feedback information, in turn resulting in the successful transfer of a newly acquired motor skill. The FRN is a negative-going component peaking approximately 145–300 ms after feedback presentation and reflects feedback processing, with more negative deflection representing greater processing. However, as FRN is a component that represents neural activation limited to the fronto-central scalp area, it cannot fully reflect the extensive cortical activities of the multiple brain regions involved in SC feedback learning. Therefore, a broader region of the brain related to the cognitive and motivational advantages of SC feedback needs to be investigated by measuring multiple components of event-related potentials (ERPs), which will provide quantitative evidence for the rationale proposed in the previous studies. For example, motivational influences can be indexed by error-related negativity (ERN; Groom et al., 2013) occurring approximately 0–100 ms post response onset associated with early error detection and error positivity (Pe; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) occurring 250–500 ms post response reflecting conscious error recognition. In addition, the P3 component is also known to be related to psychological processes, including working memory, motivation, attention, and stimulus processing (Knyazev, Savostyanov, & Levin, 2006) which occurs approximately 300–600 ms post stimulus, with larger P3 amplitude indication greater processing. In a study by Rosch and Hawk (2013), children with attention-deficit hyperactivity disorder (ADHD) demonstrated lower amplitudes of P3, ERN, and Pe during flanker stimulus tasks compared to typically developing children, which was interpreted as a result of motivational deficits associated with the disorder. However, the P3 and Pe amplitudes of the children with ADHD increased when rewards were provided during the same task. These results imply that motivational differences can be reflected by the P3, ERN, and Pe ERP components.

To date, little research has been conducted to examine the neural mechanisms of SC feedback using ERPs. Notably, unlike the previous studies in which participants have mostly been adults or children, this study targeted adolescent learners who are middle and high school students. Considering the increasing physical inactivity of teens nowadays, evidenced by shorter hours they spend on physical activities relative to elementary school students (Sallis, 2000), it is important to develop efficient practice context that can increase motivation of adolescent students toward physical activity. Therefore, the goal of this study was to examine the neural mechanisms underlying the learning advantage of SC feedback in adolescent learners. It was expected that the SC group would show superiority at processing task stimuli, response errors, and feedback compared to the YK group, which would be reflected by larger post-stimulus P3, post-response ERN and Pe, and post-feedback FRN and P3 amplitudes, respectively.

2. Methods

2.1. Participants

Forty-two middle and high school students, including 24 females (16.43 ± 2.61 years) and 18 males (17.56 ± 0.86 years), volunteered to participate in this study. All participants were self-declared right-hand dominant, had normal or corrected-to-normal vision, and were naïve to the experimental task and procedure. The participants were randomly assigned to an SC group (n = 21) or a YK group (n = 21), yoked male-to-male and female-to-female. All participants gave informed consent, and the study was approved by the Kyungpook National University Institutional Review Board (2017-0155). For compensation, all participants received a gift voucher worth approximately 18 dollars.

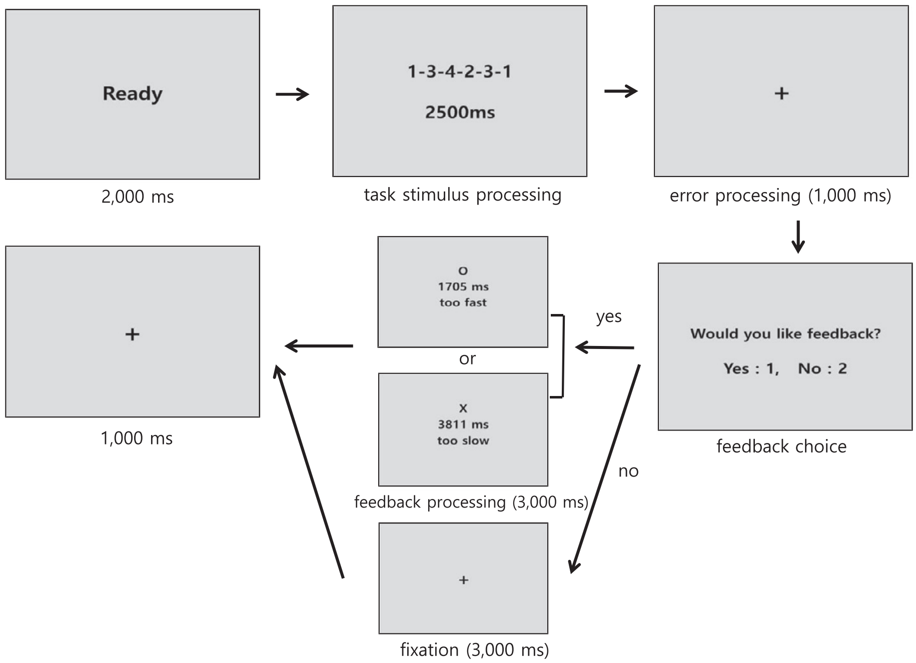

Fig. 1. Task structure for self-controlled feedback condition.

2.2. *Task and experimental paradigm*

The task was to correctly respond to a 6-digit sequence (i.e., 1-3-4-2-3-1), presented on a 45-inch screen, by pressing a series of keys on the response box with the non-dominant hand, while trying to complete the response as close to the presented goal movement time (i.e., 2500 ms) as possible. As presented in Fig. 1, a trial began with the screen presenting “ready” for 2000 ms. Upon response completion, the display changed for 2000 ms to the image of a fixation cross (“+”), followed by the next event presented differently for the SC and YK conditions. For the SC participants, a message appeared on the screen that read “would you like feedback?” with the choices to press either key 1 for “Yes” or key 2 for “No”. To request feedback, the SC participants were to press “Yes,” which led to their being presented with feedback information for 3000 ms. The feedback contained 3 types of information: (a) whether the keys were pressed correctly or incorrectly, (b) the participant’s response time, and (c) how they would have to adjust their movement time for the next trial (e.g., slightly more slowly, much more slowly, slightly faster, much faster). A fixation cross then appeared on the screen for 1000 ms. If the participant chose not to receive feedback, a fixation cross appeared on the screen for 4000 ms, equated to the duration of the feedback display in the SC condition. On completion of the 6-key response, the participants in the YK group were either presented with feedback for 3000 ms followed by 1000 ms fixation, or presented with 4000 ms fixation, based on the feedback schedule predetermined by their SC counterparts. The language used throughout the experiment, including the displays on the screen, was Korean.

2.3. *Procedure*

Upon arriving at the lab, the participants were briefed on the general purpose and procedures of the study. They were instructed to avoid any unnecessary body movements, including blinking or swallowing, while executing the experimental tasks. The participants were fitted with an electrode cap and led to a sound-attenuated chamber for the experiment. The participants in both groups were familiarized with the experimental task by 10-trial warm-up practice. In the acquisition phase, the participants were required to press the keys in the sequence 1-3-4-2-3-1 in the goal movement time of 2500 ms. The acquisition phase consisted of 4 blocks of 50 trials each, with 5 min of rest between the blocks, and each participant was required to perform a total of 200 trials. In every acquisition trial, upon completing the response, the SC participants were asked to decide whether they would like to receive feedback, whereas the YK participants, who did not have any choice over reception of feedback, automatically followed the feedback schedule predetermined by their sex-matched SC counterparts.

After 24 h, the participants came back to the laboratory to perform retention and transfer tests, in which the experimental conditions were equal for both groups. The retention test consisted of 2 blocks of 50 trials each without feedback, and the participants were required to perform the same task that they had practiced the day before during the acquisition phase. Two transfer phases followed the retention tests. In the first transfer phase, both groups were required to respond to stimuli of the same pattern (i.e., 1-3-4-2-3-1), but with a novel goal response time of 3300 ms. In the second transfer phase, the participants were asked to respond to a new pattern of 6 digits (i.e., 2-1-3-1-4-3) in the original goal response time of 2500 ms. The order of the pattern and time transfer tests was counterbalanced across and within groups. Each transfer phase included 50 trials without feedback. The task protocol used in this experiment was adopted from a study by Hansen et al. (2011), and modified to fit the goal of the present study.

2.4. EEG and behavioral data processing

2.4.1. Performance data processing

Constant error (CE), absolute constant error (ACE), variable error (VE), and the average number of incorrect trials due to an incorrect key press per block were examined to evaluate performance and learning.

2.4.2. EEG recording and signal processing

EEG data were obtained using a Biopac MP150 system (Biopac Systems Inc., Santa Barbara, CA, USA). Scalp EEG was recorded from 12 channels (Fp1, Fp2, Fz, FCz, Cz, Pz, F3, F4, C3, C4, P3, and P4) using an EEG cap (CAP100C, Biopac Systems Inc.) with tin electrodes placed according to the international 10–20 system (Jasper, 1958). The ERP and electrooculogram (EOG) signals were recorded at a sampling rate of 1000 Hz. Continuous EEG data were online-referenced to the right earlobe (A2), while the left earlobe (A1) was measured for an averaged ear reference to reduce lateral bias. The frontal midline (Fpz) served as a common ground. For all channels, impedance levels were kept below 5 kΩ using a Grass Impedance Meter (Model: EZM5, Astro-Med Inc., RI, USA). The raw EEG signals were amplified by a gain of 20,000, down sampled to 250 Hz offline, and a 0.1 Hz high-pass filter and a 30 Hz low-pass filter were applied digitally. The baseline drift was corrected by averaging each epoch. Epochs exceeding 100 μV or including artifacts or eye blinks were inspected and excluded. A total of 124 trials out of 6400 trials (1.94%) were rejected due to artifacts. To obtain ERPs, the filtered artifact-free data were segmented into time windows from 200 ms before to 1000 ms after each of the following 3 digital output signals: (a) stimulus onset, (b) response completion, and (c) feedback onset, followed by baseline correction with reference to the pre-stimulus, pre-response, and pre-feedback intervals, respectively. Each participant's average ERP was based on a minimum of 20 epochs per condition to obtain a reliable ERP average.

In an ERP analysis performed to examine the processing of primary task stimuli, the P3 amplitudes and latencies were analyzed within a time window of 300–600 ms time windows, inside which the P3 peaks were selected. Error processing was examined with response-locked ERN and Pe, with their peak amplitudes and latencies identified in a time window of 0–100 ms or 250–550 ms post-response, respectively. Feedback processing was measured by the FRN peak amplitudes and latencies within a time window of 145–300 ms post-feedback. The signal processing was performed with custom-made software developed using MATLAB 7.7 (MathWorks Inc., Natrick, MA, USA).

2.5. Statistical analysis

To determine whether SC participants requested feedback mainly after good or poor trials, the average number of errors, ACE, VE, and CE were calculated for feedback vs. no-feedback trials in a separate 2 (Group) × 4 (Block) ANOVA with repeated measures on the last factor. To analyze retention performance, independent-samples *t*-tests were separately conducted on the error values. The time and pattern transfer tests were analyzed separately in independent-samples *t*-tests with group serving as the independent variable. To assess ERP measures, separate 2 (Group) × 4 (Block) × 12 (Region: Fp1, Fp2, F3, Fz, F4, FCz, C3, Cz, C4, P3, Pz, P4) ANOVAs with repeated measures on the last 2 factors were employed for amplitudes and latencies of P3. Separate 2 (Group) × 4 (Block) × 7 (Region: F3, Fz, F4, FCz, C3, Cz, C4) ANOVAs with repeated measures on the last 2 factors were employed for amplitudes and latencies of ERN and FRN. Separate 2 (Group) × 4 (Block) × 6 (Region: C3, Cz, C4, P3, Pz, P4) ANOVAs with repeated measures on the last 2 factors were performed for Pe. In all analyses, the significance level was set at $p < 0.05$, and post hoc comparisons were conducted using Tukey's honest significant difference tests. Effect size was determined by Cohen's *d* value.

3. Results

3.1. Behavioral results

3.1.1. Acquisition

3.1.1.1. Feedback request. The SC participants requested feedback after 66% (SD = 15.9%) of trials during the first block, 62% (SD = 19.6%) during the second, 66% (SD = 19.1%) during the third, and 68% (SD = 25.4%) during the fourth block of acquisition, exhibiting no significant difference in the request frequency among the blocks ($F_{(1,\ 30)} = 0.641$, $p = 0.641$, $\eta_\rho^2 = 0.021$). Analysis of the ACEs yielded a main effect for feedback reception ($F_{(1,\ 28)} = 0.12.130$, $p = 0.002$, $\eta_\rho^2 = 0.302$, $d = 0.55$), indicating that the ACE was smaller in the feedback-received trials compared to that in the no-feedback trials.

3.1.1.2. Key-pressing error. Analysis of the key-pressing errors during acquisition revealed a significant main effect of block ($F_{(3,\ 90)} = 9.810$, $p < 0.001$ $\eta_\rho^2 = 0.246$, $d = 0.75$). Post hoc tests indicated that the participants made more key-pressing errors in the first block than in the second block, while the third and fourth blocks were performed with significantly fewer key-pressing errors compared to the first and second blocks. In addition, a significant block-by-group interaction effect ($F_{(3,\ 90)} = 3.284$, $p = 0.024$, $\eta_\rho^2 = 0.099$, $d = 0.10$) emerged. Post hoc tests revealed that the SC group made more errors in the first than in the second, third, or fourth block, while their third block contained significantly fewer errors than the second block. In contrast, the YK group made more key-pressing errors in the first and second blocks compared to the fourth block. No significant main effect for group was found ($F_{(1,$

$_{30)} = 0.106$, $p = 0.748$, $\eta_p^2 = 0.004$).

3.1.1.3. Timing error (ACE, CE, and VE). Analysis of the ACEs revealed significant main effects of group ($F_{(1, 30)} = 7.186$, $p = 0.012$, $\eta_p^2 = 0.193$, $d = 0.76$) and block ($F_{(3, 90)} = 4.783$, $p = 0.004$, $\eta_p^2 = 0.138$, $d = 0.83$). The ACE was greater in the SC group compared to that in the YK group, and significantly smaller in the third and fourth blocks than in the first or second block. No interaction effect between group and block was revealed ($F_{(3, 90)} = 0.624$, $p = 0.601$, $\eta_p^2 = 0.020$). In the analysis of CEs, no main effects of group and block, and no interaction effect between group and block were observed ($p > 0.05$). Similar to the ACE results, analysis of the VEs also revealed significant main effects of group ($F_{(1, 30)} = 7.618$, $p = 0.010$, $\eta_p^2 = 0.203$, $d = 0.75$), and block ($F_{(3, 90)} = 3.001$, $p = 0.035$, $\eta_p^2 = 0.091$, $d = 0.72$). The SC group exhibited a larger VE relative to the YK group. In addition, the participants performed with a lower VE in the fourth block than in the first block, indicating increased consistency due to practice. No interaction effect between group and block emerged ($p > 0.05$).

3.1.2. Retention

In the analysis of the retention test scores, no significant differences in ACE, CE, VE, and key-pressing errors were found between the groups ($p > 0.05$).

3.1.3. Transfer

3.1.3.1. Key-pressing error. Analysis of the key-pressing errors during the time transfer test revealed a significant main effect of group ($F_{(1, 30)} = 4.498$, $p = 0.042$, $\eta_p^2 = 0.130$, $d = 0.73$). The YK group made key-pressing errors in more trials than the SC group. Analysis of the key-pressing errors during the pattern transfer test yielded a significant main effect for group ($F_{(1, 30)} = 5.315$, $p = 0.028$, $\eta_p^2 = 0.150$, $d = 1.74$), with the YK group exhibiting key-pressing errors in more trials than the SC group. The transfer tests also showed a main effect of block ($F_{(1, 30)} = 4.301$, $p = 0.047$, $\eta_p^2 = 0.125$, $d = 1.03$), with more key-pressing errors made in the pattern transfer test compared to the time transfer test. The block-by-group interaction effect ($F_{(1, 30)} = 0.767$, $p = 0.388$, $\eta_p^2 = 0.025$) was not significant.

3.1.3.2. Timing error (ACE, CE, and VE). Analysis of the timing errors during the time transfer tests yielded a significant main effect of group for ACE ($F_{(1, 30)} = 4.546$, $p = 0.041$, $\eta_p^2 = 0.123$, $d = 0.75$) and VE ($F_{(1, 30)} = 0.4.559$, $p = 0.041$, $\eta_p^2 = 0.132$, $d = 0.75$), with the SC group exhibiting smaller ACE and VE compared to those in the YK group. Analysis of the CEs during the time transfer test revealed no significant main effect of group ($F_{(1, 30)} = 0.020$, $p = 0.888$, $\eta_p^2 = 0.001$). In the pattern transfer analysis, however, a significant main effect of group emerged for CE ($F_{(1, 30)} = 4.395$, $p = 0.045$, $\eta_p^2 = 0.128$, $d = 0.74$), while those for ACE ($F_{(1, 30)} = 3.080$, $p = 0.089$, $\eta_p^2 = 0.093$) and VE ($F_{(1, 30)} = 2.968$, $p = 0.095$, $\eta_p^2 = 0.090$) did not reach significance. In addition, examining the difference in timing errors between the 2 transfer blocks revealed significant main effects of block for ACE ($F_{(1, 30)} = 7.396$, $p = 0.011$, $\eta_p^2 = 0.193$, $d = 0.39$), CE ($F_{(1, 30)} = 9.182$, $p = 0.005$, $\eta_p^2 = 0.234$, $d = 0.46$), and VE ($F_{(1, 30)} = 0.6.132$, $p = 0.019$, $\eta_p^2 = 0.170$, $d = 0.33$), with greater timing errors made during the time transfer test compared to the pattern transfer test. The block-by-group interaction effects were not significant for ACE ($F_{(1, 30)} = 1.068$, $p = 0.310$, $\eta_p^2 = 0.034$), CE ($F_{(1, 30)} = 3.265$, $p = 0.081$, $\eta_p^2 = 0.098$), and VE($F_{(1, 30)} = 1.504$, $p = 0.230$, $\eta_p^2 = 0.048$). The mean (M) and standard deviation (SD) for all behavioral results are presented in Table 1.

3.2. ERP results

3.2.1. Stimulus-locked ERPs

3.2.1.1. P3 amplitude. Analyses of post-stimulus P3 amplitudes yielded significant main effects for block ($F_{(3, 90)} = 4.115$, $p = 0.009$, $\eta_p^2 = 0.121$, $d = 0.25$) and region ($F_{(11, 330)} = 153.289$, $p < 0.001$, $\eta_p^2 = 0.836$, $d = 0.41$). Post hoc tests revealed that the P3 amplitude was larger in the following orders: block 2 > block 3 > block 1 and block 4, and frontal > central > parietal sites. The

Table 1

The means (M) and standard deviations (SD) of timing error: the absolute constant errors (ACE), constant errors (CE), and variable errors (VE), average numbers of key-pressing errors, and feedback request proportions per block in the self-control (SC) and yoked (YK) groups.

		Block 1		Block 2		Block 3		Block 4		Retention		Time Transfer		Pattern Transfer	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
ACE	SC	280.1*	119.5	282.3*	206.9	219.7	129.8	219.2	139.3	268.6	121.2	316.1*	154.8	232.9	125.2
	YK	185*	30.2	167.5*	30.2	150.6	47	138.5	48.8	347	318.8	640.1*	587.8	454.9	490.3
CE	SC	6.2	95.8	36	169.2	−2.9	147.1	−20.1	165.3	133.3	182.4	−7.3	309.2	80.6*	181.7
	YK	−38.7	73.7	−10.6	101.3	−17.9	72.8	−17.9	75.5	264.9	358.1	24.7	841.5	372.2*	525.8
VE	SC	404.7*	172	414	344.6	318.1	247.2	308.4	192.7	324.6	145	379*	174.6	316.4	162.2
	YK	271.8*	83.2	233.1	104.4	216.8	85.4	185	60.9	347	319	731.8*	637.8	546.5	509
Error/Block	SC	7.9*	5.7	5.2*	3.9	3.1	2.7	4	3.9	2	2.3	1.3*	1.5	2.4*	1.5
	YK	5.4*	5.5	5.4*	6.6	4.5	6	3	3.7	3.5	5.1	4.3*	5.6	5.1*	1.6
Feedback Request (%)	SC	66	0.2	62	0.2	66	0.2	68	0.3						

* $P < 0.05$.

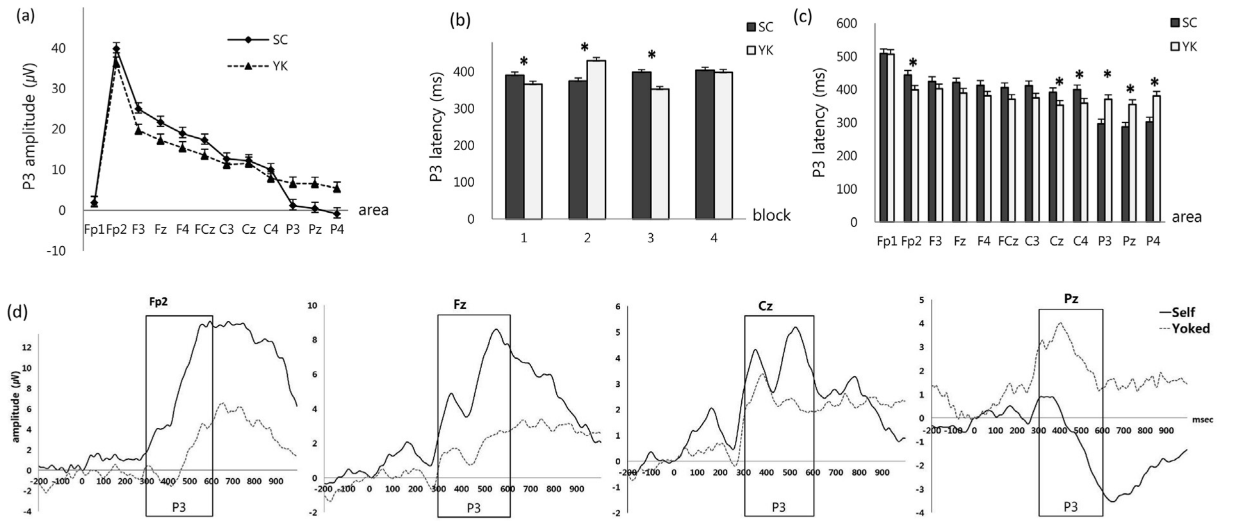

Fig. 2. Post-stimulus ERPs and average waveforms (a) Post-stimulus P3 amplitude by group and area (b) Post-stimulus P3 latency by group and block (c) Post-stimulus P3 latency by group and area (d) Stimulus-locked P3 waveform of the SC and YK groups at Fp2, Fz, Cz, and Pz. The SC group showed larger P3 amplitudes at F3 and Fz, and smaller P3 amplitudes at P3, Pz, and P4 compared to those in the YK group. The SC group exhibited a shorter P3 latency than the YK group in block 2, while the YK group showed shorter P3 latencies than the SC group in blocks 1 and 3. The YK group showed shorter P3 latencies at Fp2, Cz, and C4 than the SC group, while the SC group exhibited shorter latencies in the P3, Pz, and P4 areas.

main effect of group was found not to be significant ($F_{(1,\ 30)} = 0.141$, $p = 0.710$, $\eta_\rho^2 = 0.005$). Significant group × region ($F_{(11,\ 330)} = 6.265$, $p < 0.001$, $\eta_\rho^2 = 0.173$, $d = 0.35$), block × region ($F_{(33,\ 990)} = 2.542$, $p < 0.001$, $\eta_\rho^2 = 0.087$, $d = 0.78$), and group × block × region ($F_{(33,\ 990)} = 2.098$, $p < 0.001$, $\eta_\rho^2 = 0.065$, $d = 0.91$) interaction effects emerged. Post hoc test results showed that the SC group exhibited larger P3 amplitudes at F3 and Fz, and smaller P3 amplitudes at P3, Pz, and P4 compared to those in the YK group in block 2 (Fig. 2.a.). The group × block interaction effect did not reach significance ($F_{(3,\ 90)} = 0.743$, $p = 0.529$, $\eta_\rho^2 = 0.024$).

3.2.1.2. P3 latency. Analyses of the post-stimulus P3 latencies yielded a significant main effect for region ($F_{(11,\ 330)} = 39.751$, $p < 0.001$, $\eta_\rho^2 = 0.570$, $d = 0.39$). Post hoc tests revealed that the P3 latency was the longest at Fp1, and the parietal region exhibited a shorter latency than the prefrontal, frontal, and central regions. No significant main effects were found for group ($F_{(1,\ 30)} = 0.190$, $p = 0.666$, $\eta_\rho^2 = 0.006$) and block ($F_{(3,\ 90)} = 1.336$, $p = 0.268$, $\eta_\rho^2 = 0.043$). Significant group × block ($F_{(3,\ 90)} = 3.103$, $p = 0.031$, $\eta_\rho^2 = 0.094$, $d = 0.48$), block × region ($F_{(33,\ 990)} = 2.278$, $p < 0.001$, $\eta_\rho^2 = 0.102$, $d = 0.32$), group × region ($F_{(11,\ 330)} = 9.839$, $p < 0.001$, $\eta_\rho^2 = 0.247$, $d = 0.39$), and group × block × region ($F_{(33,\ 990)} = 2.278$, $p < 0.001$, $\eta_\rho^2 = 0.071$, $d = 0.62$) interaction effects were observed. Post hoc tests revealed that the SC group exhibited a shorter post-stimulus P3 latency than the YK group in block 2, while the YK group showed shorter P3 latencies than the SC group in blocks 1 and 3 (Fig. 2.b.). In addition, the YK group showed shorter P3 latencies at Fp2, Cz, and C4 than the SC group, while the SC group exhibited shorter latencies in the P3, Pz, and P4 regions (Fig. 2.c). The stimulus-locked ERP waveforms are presented in Fig. 2.d.

3.2.2. Response-locked ERPs

3.2.2.1. ERN amplitude. Analyses of the post-response ERN amplitudes yielded a significant main effect for region ($F_{(6,\ 180)} = 6.282$, $p < 0.001$, $\eta_\rho^2 = 0.173$). Post hoc tests revealed that the ERN amplitude at C3 was smaller than those at F3 and Fz. No other main effects or interactions were observed.

3.2.2.2. ERN latency. In the analyses of post-response ERN latencies, no significant main effects for group ($F_{(1,\ 30)} = 0.056$, $p = 0.814$, $\eta_\rho^2 = 0.814$), block ($F_{(3,\ 90)} = 0.360$, $p = 0.782$, $\eta_\rho^2 = 0.012$), and region ($F_{(6,\ 180)} = 0.227$, $p = 0.968$, $\eta_\rho^2 = 0.008$) were found. A significant group × block interaction effect emerged ($F_{(3,\ 90)} = 3.179$, $p = 0.028$, $\eta_\rho^2 = 0.096$, $d = 0.61$). Post hoc tests revealed that the YK group exhibited a shorter ERN latency than the SC group in block 2, while the SC group showed a shorter ERN latency than the YK group in block 4 (Fig. 3.a.). No other interaction effects were observed.

3.2.2.3. Pe amplitude. In the analyses of post-response Pe amplitudes, significant main effects of group ($F_{(1,\ 30)} = 6.517$, $p = 0.016$, $\eta_\rho^2 = 0.178$, $d = 3.61$) and region ($F_{(5,\ 150)} = 4.099$, $p = 0.002$, $\eta_\rho^2 = 0.120$, $d = 2.95$) emerged. Post hoc tests showed that the YK group exhibited a larger Pe amplitude than the SC group. C3 and Cz exhibited larger amplitudes than C4 and P4, while the amplitude at P3 was larger than that at P4. The main effect of block ($F_{(3,\ 90)} = 0.351$, $p = 0.789$, $\eta_\rho^2 = 0.012$) did not reach significance. Significant group × block ($F_{(3,\ 90)} = 2.672$, $p = 0.052$, $\eta_\rho^2 = 0.082$, $d = 0.70$), group × region ($F_{(5,\ 150)} = 3.914$, $p = 0.002$, $\eta_\rho^2 = 0.115$, $d = 0.85$), and group × block × region ($F_{(15,\ 450)} = 2.069$, $p = 0.010$, $\eta_\rho^2 = 0.065$, $d = 0.78$) interaction effects emerged. Post hoc tests revealed that the YK group exhibited larger Pe amplitudes than the SC group in blocks 1, 2, and 3, but

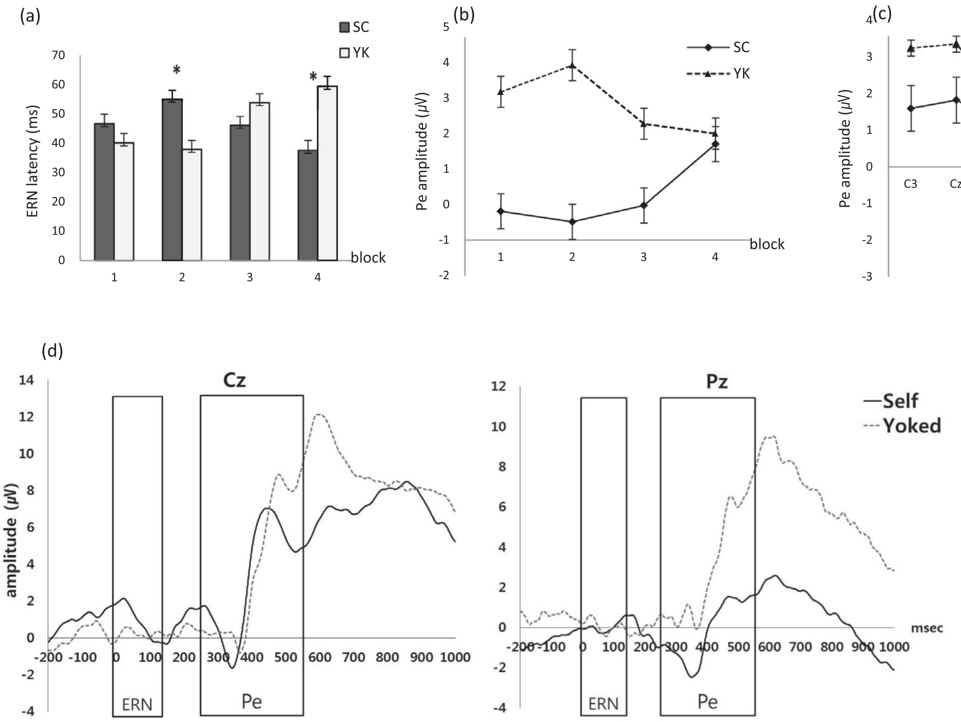

Fig. 3. Post-response ERPs and waveforms (a) Post-response ERN latency by group and block (b) Post-response Pe amplitude by group and block (c) Post-response Pe amplitude by group and area (d) Response-locked Pe waveform of the SC and YK groups at Cz and Pz. The YK group showed a shorter ERN latency than the SC group in block 2, while the SC group showed a shorter ERN latency than the YK group in block 4. The YK group exhibited larger Pe amplitudes than the SC group in blocks 1, 2, and 3. The Pe amplitudes in the YK group were larger than those in the SC group at P3, Pz, and P4.

not in block 4 (Fig. 3.b.). In addition, the Pe amplitudes in the YK group were larger than those in the SC group at P3, Pz, and P4 (Fig. 3.c.). No significant interaction effect was observed between block and region ($F_{(15,\ 450)} = 1.266$, $p = 0.220$, $\eta_\rho^2 = 0.041$). The response-locked ERP waveforms are presented in Fig. 3.d.

3.2.3. Feedback-locked ERPs

3.2.3.1. FRN amplitude. Analyses of the post-feedback FRN amplitudes revealed no significant main effects of group ($F_{(1,\ 30)} = 0.281$, $p = 0.600$, $\eta_\rho^2 = 0.009$), block ($F(3, 90) = 0.624$, $p = 0.601$, $\eta_\rho^2 = 0.020$) and region ($F_{(6,\ 180)} = 1.653$, $p = 0.188$, $\eta_\rho^2 = 0.045$). In addition, no significant interaction effects were observed.

3.2.3.2. FRN latency. Analyses of the post-feedback FRN latencies yielded no significant main effects for group ($F_{(1,\ 30)} = 0.281$, $p = 0.600$, $\eta_\rho^2 = 0.009$), block ($F_{(3,\ 90)} = 0.624$, $p = 0.601$, $\eta_\rho^2 = 0.020$), and region ($F_{(6,\ 180)} = 0.349$, $p = 0.525$, $\eta_\rho^2 = 0.010$). No significant interaction effect emerged.

3.2.3.3. P3 amplitude. Analyses of the post-feedback P3 amplitudes yielded a significant main effect for region ($F_{(11,\ 330)} = 24.848$, $p < 0.001$, $\eta_\rho^2 = 0.453$, $d = 51$). Post hoc tests indicated that frontal regions (F3 and Fz) exhibited larger P3 amplitudes than central regions (C3 and C4). No significant main effects of group ($F_{(1,\ 30)} = 3.136$, $p = 0.087$, $\eta_\rho^2 = 0.095$) and block ($F_{(3,\ 90)} = 0.165$, $p = 0.920$, $\eta_\rho^2 = 0.005$) were found. Significant group × region ($F_{(11,\ 330)} = 9.250$, $p < 0.001$, $\eta_\rho^2 = 0.236$, $d = 0.79$) and group × block × region ($F_{(33,\ 990)} = 2.451$, $p < 0.001$, $\eta_\rho^2 = 0.076$, $d = 0.67$) interaction effects were found. Post hoc tests indicated that the SC group exhibited larger P3 amplitudes than the YK group at the Fp2, F3, Fz, and F4 sites, while the YK group showed larger amplitudes than the SC group at Pz and P4 (Fig. 4.a.). No significant interaction effects were observed between group and block ($p = 0.129$), and block and region ($p = 0.971$).

3.2.3.4. P3 latency. In the analyses of post-feedback P3 latencies, a significant main effect of region emerged ($F_{(11,\ 330)} = 13.037$, $p < 0.001$, $\eta_\rho^2 = 0.303$, $d = 0.41$). Post hoc tests revealed that the frontal regions showed longer P3 latencies than the parietal regions. No other significant main effects or interactions were found. The feedback-locked ERP waveforms are presented in Fig. 4.b.

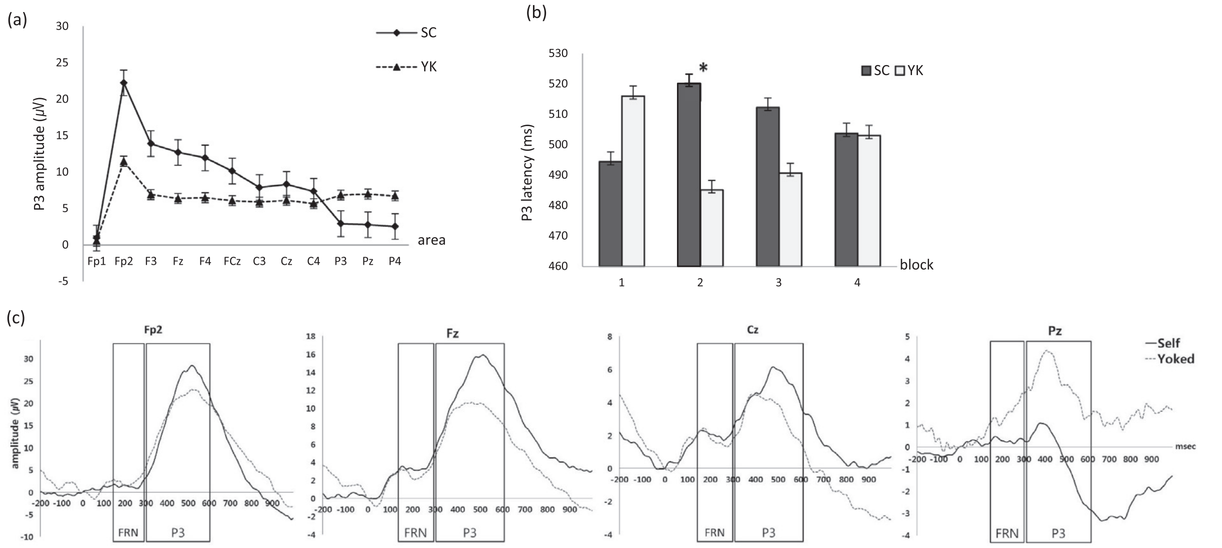

Fig. 4. Post-feedback ERPs and waveforms (a) post-feedback P3 amplitude by group and area (b) Feedback-locked P3 amplitude of the SC and YK groups at Fp2, Fz, Cz, and Pz. The SC group exhibited larger P3 amplitudes than the YK group at the Fp2, F3, Fz, and F4 sites, while the YK group showed larger amplitudes than the SC group at Pz and P4.

4. Discussion

The present study aimed to investigate the learning advantage of SC feedback and its underlying neural mechanisms. As predicted, the SC group demonstrated superior performance in the transfer phase, exhibiting higher timing and key-pressing accuracies than the YK group in time and pattern transfer tests. However, no significant differences in retention accuracy were found.

4.1. Behavioral measures (acquisition, retention, an transfer)

The superior performance of the SC group in transfer, but not in retention, is consistent with the findings of Grand et al. (2015). A transfer test has been suggested to be more sensitive than a retention test in capturing learning effects, as it requires participants to adapt to a novel context (Chiviacowsky & Wulf, 2002; Post et al., 2011). Interestingly, the YK group exhibited superior performance compared to the SC group during the acquisition phase. Though the SC participants committed more errors than the YK participants during acquisition, they outperformed the YK subjects on the transfer tests, which supports SC feedback being beneficial for learning. The inferior performance of the SC group during acquisition may be attributable to the increased cognitive demands of having to perform the task and control one's feedback reception at the same time. Bund and Wiemeyer (2004) reported that the SC practice condition created greater strain on cognition, requiring cognitive resources to split between task performance and self-control. However, once the performance conditions were equated by eliminating the requirement to make decisions about feedback reception, the SC participants performed as well as the YK participants in retention and demonstrated superior performance in transfer.

Analyses of the amplitudes and latencies of the ERP measures yielded results that indicated differences between the SC and YK groups in stimulus, response, and feedback processing, as reflected by the post-stimulus P3, post-response ERN and Pe, and post-feedback P3, respectively. Our interpretations of the results for each ERP component are discussed below.

4.2. Stimulus processing

In the analysis of the post-stimulus P3 potentials, the SC group exhibited larger amplitudes than the YK group in frontal regions. Since the P3 amplitude is typically associated with task stimulus processing, this result may indicate that the SC group engaged in more active cognitive processing of the stimulus compared to the YK group. These results support the cognitive benefit of SC feedback speculated in numerous previous studies (Hartman, 2007; Patterson et al., 2011; Wulf et al., 2001) that proposed that more efficient and deeper information processing was the reason for the superior learning effect of SC feedback. This interpretation is supported by Polish (2007), who suggested that the P3 amplitude could be seen as an index of the amount of cognitive resources allocated to executing a cognitive task, with increased mental effort producing an increase in the P3 amplitude. Thus, the SC participants may have devoted more cognitive effort than the YK participants to performing the task. The greater amount of cognitive effort observed in the SC subjects may be attributable to their experimental condition, which required them to make decisions whether to receive feedback after each trial while trying to perform the task as accurately as possible. This requirement might have increased the SC participants' cognitive burdens, leading to heightened P3 amplitudes. Bund and Wiemeyer (2004) support this possibility by arguing that the SC practice condition imposes greater strain on cognition, requiring decision making as well as stimulus monitoring, evaluation, and modification. Therefore, in acquisition, cognitive resources tend to split between learning itself and the self-control process. In retention and transfer, however, the same task conditions were created for the SC and YK groups, equating the cognitive strain for both groups and thus enabling the SC group to perform as well as, or better than, the YK group.

The higher P3 amplitude observed in the SC group can also be explained in association with the motivational relevance of, or attachment to, the task. The effects of motivation on the P3 amplitude have been extensively addressed in the existing studies. A study by Kleih, Nijboer, Halder, and Kübler (2010) revealed that increasing the incentive value of the stimulus resulted in increased P3 amplitudes. In a study by Carrillo-de-la Pena and Cadaveira (2000), the P3 amplitude increased when the task was performed following motivating instructions. Thus, the higher P3 amplitude observed in the SC group demonstrates that the SC feedback condition presumably enhances the motivation to perform well. The motivational benefit of SC feedback is also supported by the SC participants' preference for feedback after good trials relative to bad trials. These findings may provide empirical evidence for the hypothesis, put forth by Chen et al. (2002), that increased motivation associated with self-control benefits the cognitive process of learning.

Despite the higher cortical activation observed at the frontal regions in the SC group, the SC participants exhibited smaller amplitudes with shorter latencies at the parietal regions compared to those in the YK group. This pattern of increased activation in some regions but decreased activation in other regions have been reported in previous studies (Gevins & Smith, 2000; Li, Gratton, Yao, & Knight, 2010). For instance, in the study by Gevins and Smith (2000), high-ability subjects showed smaller prefrontal activation with higher parietal activation compared to their low-ability counterparts during working memory task. The parietal region is associated with automatic transformation of visual information into the motor domain (Deiber et al., 1997). Therefore, the reduced parietal activity with shorter latencies in the SC group implies that the SC participants processed the task stimuli less automatically but more deliberately than the YK group. Similarly, in the study by Rypma et al. (2006), relatively high-performing group exhibited higher parietal activation, relying on automatic processing, while low-performing group showed higher prefrontal activation, reflecting increased executive control for optimal task performance. As the behavioral results of the present study showed that YK group performed better than the SC group in acquisition, it appears that the stimulus processing under self-controlled feedback condition was more effortful, while the yoked feedback condition allowed for more automatic stimulus processing.

4.3. Error processing

Analysis of the post-response Pe revealed that the YK group exhibited larger Pe amplitudes than the SC group. Pe is an ERP potential known to reflect conscious error recognition, error evaluation (Overbeek, Nieuwenhuis, & Ridderinkhof, 2005), and change in response strategy following an error and its subjective or emotional assessment (Falkenstein et al., 2000). Therefore, the larger Pe amplitude observed in the YK group compared to the SC group implies that the YK participants might have processed their response errors more actively than the SC participants. This finding contradicts the argument of Chiviacowsky and Wulf (2005), who speculated that spontaneous error estimations might contribute to the beneficial effects of SC practice. In the present study, the YK group was not given the freedom to receive feedback depending on their needs, unlike the SC group. In an effort to achieve good performance in a control-deprived condition, it is possible that the YK participants relied on their own evaluations of response errors, producing larger Pe amplitudes compared to the SC participants, who could see their performance results whenever they wanted. The error-related ERP results obtained in the present study are consistent with a previous study that reported unaffected ERN accompanied by significantly reduced Pe when participants were unaware of their mistakes, suggesting that Pe is related to the subjective awareness of a performance error (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001).

The expected negative deflections of the ERN potentials were not observed in this study, which might be attributable to the characteristics of the experimental task, in which the accuracy of the task performance was designed to be assessed by key-pressing correctness in association with the response timing error. To clearly measure the effect of error processing via ERN, the incorrect trials need to be distinguished from the correct ones. However, since the timing measures such as ACE, CE, and VE represent the value of a specific point on a continuous time line, and the key-pressing measures also have a correctness range of 1 to 6 wrongly pressed keys, it was impossible to simply divide the values into 'correct' and 'incorrect'. These varying levels of correctness were not fully considered in conducting the present study. Therefore, to investigate the mechanism of error processing in subjects with SC feedback, future studies need to adopt an experimental task the results of which can be identified as correct/incorrect and analyze the ERN components more thoroughly.

4.4. Feedback processing

The SC group exhibited larger post-feedback P3 amplitudes than the YK group at the pre-frontal and frontal regions. The P3 amplitude reflects the amount of information transferred to working memory (Polich & Kok, 1995). Therefore, an enhanced P3 might indicate increased demands on the cognitive processes of SC participants (e.g., working memory and attention) during interpretation of the feedback they received. The pattern of the enhanced post-feedback P3 amplitudes was also observed in the analysis of post-stimulus P3 amplitudes in the present study. This result suggests that the SC group not only engaged in deeper processing of the task stimuli but also processed feedback information more actively compared to the YK group. The superior stimulus and feedback processing of the SC group, evidenced by the stronger P3 activation, may lend support to the speculation of Janelle et al. (1995), who attributed the advantage of SC feedback to deeper information processing that occurs when learners have control over learning.

In addition, higher prefrontal activation in the SC group compared to that in the YK group during feedback processing may explain the superior self-regulation of the SC subjects. It is accepted that self-control of physical activity involves prefrontal activation, which is linked to executive functions including self-control, selective attention, planning, and mental flexibility (Hofmann, Schmeichel, & Baddeley, 2012). These functions are critical for successful self-regulation, enabling learners to maintain goals throughout practice, detect conflict or discrepancy, and adjust behavioral control accordingly (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Therefore, the higher prefrontal activation found in the SC group in the present study may provide a neurophysiological explanation for the advantage of SC feedback, i.e., that it enhances self-control of the learner.

Despite the higher cortical activation in the SC subjects observed at the prefrontal and frontal regions, they exhibited lower activation at the parietal regions compared to the YK group. The reduced parietal activity in the SC group during feedback processing, similar to the pattern observed during task stimulus processing, implies that the SC group processed visual stimuli more effortfully and less automatically than the YK group (Gevins & Smith, 2000).

Contrary to the prediction, the FRN amplitude and latency were not significantly different between the SC and YK groups. The absence of significant differences of FRN between the groups might be related to the quality of feedback information used in the experiment. Although FRN is known to reflect feedback processing, it is more sensitive to negative (rather than positive) and unexpected (rather than expected) feedback. Larger FRN amplitudes are elicited with undesirable events than with desirable events (Kóbor et al., 2015), and with irrelevant than relevant events (Walentowsk, Moors, Paul, & Pourtois, 2016). However, the feedback information presented to the participants in the present study consisted of knowledge of results (KR) about the accuracy and movement time of the previously completed response, which is a relatively neutral event, not being particularly negative or unexpected. This feedback feature might account for the undifferentiated FRN between the SC and YK groups. However, differences in the P3 components emerged that explained the differences in the cognitive processing of feedback information between the SC and YK groups. P3 is known to be more sensitive than FRN to cognitive control and thus represents a more elaborate evaluation of outcomes (Euser et al., 2013).

5. Summary

The purpose of this study was to examine neural mechanisms of self-controlled feedback underlying its learning advantages. Forty-two adolescent participants volunteered in the experiment, and were randomly assigned to either the self-control (SC, n = 21) group or the yoked (YK, n = 21) group. The six-key pressing task with a goal movement time was adopted as the experimental task in the acquisition, retention, and transfer phases. In the acquisition phase, the SC participants performed the task under their own control of seeing the KR feedback, while the YK participants did not have any choice over feedback reception. 24-hours-delayed retention and transfer tests were conducted, where KR feedback was not provided. The correctness of key-pressing as well as timing accuracy was measured during the acquisition, retention, and transfer phases. Exclusively in the acquisition phase, participants' cognitive processing (ERP) was measured, time-locked to stimulus presentation, response completion, and feedback presentation.

The analyses of behavioral results showed that the YK group exhibited superior performance than the SC group during acquisition. However, the SC group demonstrated superior performance in transfer, though such differences did not reach significance in retention. In the analysis of post-stimulus P3 potentials, larger amplitude was observed in the SC group versus the YK group, which indicates that the SC group processed the task stimulus more actively compared to the YK group. Considering the motivational relevance of the P3 amplitude, the SC group might have had higher motivation to perform well and stronger attachment to the task while practicing a new motor skill. In the analysis of post-response Pe potentials, the YK group exhibited larger amplitudes than the SC group, which shows that the YK participants were more active in processing response errors compared to the SC participants. It appears that the YK participants relied more heavily on their own evaluation of response errors in an effort to achieve good performance under the control-deprived condition, as compared to the SC participants who could see results whenever they wanted. The analysis of post-feedback P3 potentials revealed larger P3 amplitudes with shorter latencies in the SC group relative to the YK group, reflecting higher demands on the cognitive processes of the SC participants for interpretation of the feedback they received. In addition, the SC group showed superiority at self-regulation over the YK group, exhibiting higher prefrontal activation, which is related to self-control, selective attention, planning, and mental flexibility, during task stimulus processing and feedback processing. Contrary to the higher post-stimulus and post-feedback P3 amplitudes in the prefrontal, frontal and central regions, the SC group exhibited smaller activation than the YK group in the parietal regions. This suggests that that the SC participants processed information more effortfully and in a less automatic manner than the YK group. Through these findings, the present study aims to provide an understanding about the neural mechanisms underlying self-controlled feedback.

6. Conclusions

This study examined the effects of SC feedback on motor learning and the underlying neural mechanisms. A beneficial effect of SC feedback was found in the transfer phase, which requires adjusting performance to a novel task. Neurophysiological investigation revealed that SC feedback is advantageous for stimulus and feedback processing, which explains the superiority of SC feedback in cognitive processing, motivation, and self-regulation. However, SC feedback may have a weakness in spontaneous error recognition. An applied perspective of the findings of the present study supports the use of SC feedback as a guidance method for teaching motor skills. This study provided a neurophysiological understanding of the learning advantages of SC feedback using key-pressing tasks in association with timing goals in a laboratory setting. However, further studies would be more convincing if they adopted experimental tasks in field settings, which may ensure greater validity and generalizability of the psychophysiological findings of this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.04.009.

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