# Performance monitoring and response conflict resolution associated with choice stepping reaction tasks

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## Abstract

Choice reaction requires response conflict resolution, and the resolution processes that occur during a choice stepping reaction task undertaken in a standing position, which requires maintenance of balance, may be different to those processes occurring during a choice reaction task performed in a seated position. The study purpose was to investigate the resolution processes during a choice stepping reaction task at the cortical level using electroencephalography and compare the results with a control task involving ankle dorsiflexion responses. Twelve young adults either stepped forward or dorsiflexed the ankle in response to a visual imperative stimulus presented on a computer screen. We used the Simon task and examined the error-related negativity (ERN) that follows an incorrect response and the correct-response negativity (CRN) that follows a correct response. Error was defined as an incorrect initial weight transfer for the stepping task and as an incorrect initial tibialis anterior activation for the control task. Results revealed that ERN and CRN amplitudes were similar in size for the stepping task, whereas the amplitude of ERN was larger than that of CRN for the control task. The ERN amplitude was also larger in the stepping task than the control task. These observations suggest that a choice stepping reaction task involves a strategy emphasizing post-response conflict and general performance monitoring of actual and required responses and also requires greater cognitive load than a choice dorsiflexion reaction. The response conflict resolution processes appear to be different for stepping tasks and reaction tasks performed in a seated position.

**Keywords:**

choice stepping reaction task; error-related negativity; correct-response negativity; anticipatory postural adjustments; electroencephalography

## Introduction

Prevention of falls in the elderly population is a great public health focus. More than 30% of community-dwelling elderly adults >65 years of age fall at least once a year (Tinetti et al. 1988) or even in 6 months (Cevizci et al. 2015). The consequences of falls often include severe injuries and sometimes death (Kannus et al. 2005). One of the risk factors recently identified to be related to falls in the elderly is poor volitional stepping performance (Lord and Fitzpatrick 2001; St George et al. 2007; Pijnappels et al. 2010). Indeed, delayed execution time during volitional choice stepping was found to be a reliable and valid predictor of future falls (Ejupi et al. 2014; Schoene et al. 2014; Delbaere et al. 2015).

The postural control required for volitional stepping includes anticipatory postural adjustments (APAs) that precede a lift off of the swing leg. During transition from a stable bipedal position to an unstable single-leg position, the tibialis anterior (TA) muscles co-activate and the center of pressure (COP) posteriorly and mediolaterally transfers toward the swing leg (Winter 1995; Halliday et al. 1998). This posterolateral transfer then creates the forces to propel the COP toward the standing leg and, thus, is essential for forward progression (Breniere and Do 1991; Elble et al. 1994; Burleigh and Horak 1996). Furthermore, APAs have been reported to be modulated by aging and several pathological conditions (Jacobs et al. 2009; Mancini et al. 2009; Kanekar and Aruin 2014), signifying their sensitivity and importance in the control of stepping movements.

One APA modulation that takes place while implementing volitional choice stepping is an incorrect initial transfer of COP toward the standing leg, which is defined as an APA error. It is supposed to account for delayed step execution because incorrect weight shift has to be corrected prior to step initiation (Cohen et al. 2011).

An increase in APA error rates with visual and auditory interferences, as well as ageing, suggests that executive function, especially inhibitory control, is responsible for this phenomenon (Sparto et al. 2013; Uemura et al. 2013; Watanabe et al. 2015). Given that poor executive function is a key contributor to incorrect APAs and delayed step execution, information processing and performance monitoring seem be the vital components of accurate judgments and successful recovery of postural responses. It is, therefore, essential to uncover the temporal nervous control involved in choice stepping behavior.

Information processing and performance monitoring are partly completed by the anterior cingulate cortex (ACC) that serves various cognitive control functions (Botvinick et al. 2001; Gehring and Fencsik 2001). Previous studies have identified a negative electroencephalographic (EEG) deflection possibly generated from the ACC, shortly after the error is committed, in an event-related brain potential (ERP) component (e.g., Gehring et al. 1993; Schreiber et al. 2011; Masaki et al. 2012). This is known as error-related negativity (ERN) and is normally larger than correct-related negativity (CRN) that can be found after a correct response. The functional significance of ERN was initially thought to be associated with error detection (Falkenstein et al. 1991; Gehring et al. 1993). Alternatively, the ERN was proposed to be a signal reflecting a response conflict due to a finding of the CRN (Vidal et al. 2000). Although the exact role and origin of the ERN and CRN remain a matter for debate (e.g., Van Veen and Carter 2002; Luu et al. 2003; Debener et al. 2005), it is suggested that those two response-related negativities both reflect general performance monitoring, and the error signal is additionally reflected by the ERN (Falkenstein et al. 2000; Endrass et al. 2012). Furthermore, there is a growing body of literature describing the factors that modulate these negativities. For instance, it has been reported that the ERN is sensitive to such factors as response forces, interference effects of stimulus-response compatibility (SRC) tasks, and error awareness (e.g., Masaki et al. 2012; Armbrecht et al. 2013; Navarro-Cebrian et al. 2013), whereas the CRN is sensitive to response uncertainty and strategy adjustments (e.g., Scheffers and Coles 2000; Pailing and Segalowitz 2004; Bartholow et al. 2005).

In contrast to choice reaction time (CRT) tasks involving upper-limb extremities, there are limited studies on conflict resolution at the cortical level with foot responses (Holroyd et al. 1998). In the area of a volitional stepping, we found no studies that investigated the conflict resolution processes at the cortical level. It is possible that distinct information processing and performance monitoring could take place during choice responses in a standing position that require higher cognitive and motor controls than those performed in a seated position (Lacour et al. 2008). The maintenance of balance that is necessary during a stepping movement may interfere with the conflict resolution and its cognitive process, inferring the potential implementation of strategic changes. Therefore, evaluating the cortical activities during volitional choice stepping could provide new insights into the integration of postural and executive functions. ERP components, such as ERN and CRN, may further serve as effective electrophysiological markers for declined postural control performance since abnormalities in those ERPs are reported in older individuals and those with movement disorders (e.g., Falkenstein et al. 2001; Stemmer et al. 2007). Accordingly, the purpose of the present study was to examine how response conflicts are resolved at the cortical level during volitional choice stepping. We had foot dorsiflexion serve as a control limb response (Vidailhet et al. 1993; Yazawa et al. 1997), during which ERN amplitude is expected to be larger than CRN, to prove that our experimental paradigm would elicit ERN and CRN. We hypothesized that if APA errors are processed during a choice stepping reaction task in the same manner as the foot dorsiflexion reaction, then the amplitude of ERN would be larger than CRN during a choice stepping reaction task.

## Methods

### *Subjects*

Twelve young adults (five females, mean age ± SD = 22.8 ± 1.7 years) recruited from Nagoya University School of Health Sciences participated in this study. They all reported that they were free of any history of neurological, psychiatric, or orthopedic disorders that could affect stepping behavior, and all had normal or corrected-to-normal vision. The experimental procedures were in accordance with the Declaration of Helsinki. After detailed explanation of the experiment, each subject provided written informed consent.

### *Experimental protocol*

The experiment consisted of two tasks: a volitional choice stepping reaction time task and a CRT task with ankle dorsiflexion responses. In the stepping task, the subjects stood barefoot on a force plate and maintained a stationary standing position with both arms at their sides. Each foot was placed 5 cm away from a centerline drawn on the force plate. Subject weight was distributed equally, and maintained by monitoring the COP position online. The subjects fixed their gaze on a cross sign presented at the center of a computer screen set just below eye level at a 1.0-m distance. They were instructed to step forward as quickly and accurately as possible in response to a visual imperative stimulus of an arrow appearing on the same screen and then return to the same stationary starting position. The subjects stepped forward with the corresponding side onto a wood plate that was placed in front of the force plate and then subjects brought the other side alongside the first foot. In the CRT task with ankle dorsiflexion responses, subjects sat on an armchair and were instructed to gaze upon a cross sign presented at the center of the computer screen at a 1.0-m distance. They dorsiflexed the ankle as quickly and accurately as possible in response to the same stimulus used in the stepping task.

For both tasks we applied a Simon task that comprised of congruent (response and location of the stimulus are the same) and incongruent (response and location of the stimulus are different) conditions (Simon 1990), since this had reliably induced a sufficient number of APA errors in previous studies (Sparto et al. 2013; Watanabe et al. 2015). In each trial, one of four arrow stimuli (two locations × two directions) was pseudorandomly presented (Fig. 1), and the response side (left or right) was determined based on the pointing direction of the arrow, irrespective of the arrow location. The visual imperative stimulus was presented for 500 ms, and one single trial was 7-s long. The cross sign was presented throughout the experiment (Fig. 1). Following a practice block of about 50 trials, subjects completed four blocks of 50 trials (25 congruent and 25 incongruent conditions) with short breaks between them for each task. The order of tasks was interchanged randomly among subjects.

### *Data recording*

We recorded EEG and electromyographic (EMG) signals for the two tasks. The EEG signals were recorded with Ag/AgCl electrodes using a digital EEG instrument (Nihon Kohden, Tokyo, Japan). They were amplified, filtered at 0.01–200 Hz, and stored for offline analysis. The recording locations were Fz, FCz, and Cz, determined according to the International 10–20 system. Each electrode was referenced to the average of the right and left ear lobes. A vertical and horizontal electrooculogram (EOG) was also recorded using electrodes placed above and lateral to the right eye. The impedances were maintained below 5 kΩ throughout the experiment. Surface EMG signals were recorded from the TA muscles bilaterally using a conventional EMG machine (Nihon Kohden, Tokyo, Japan). The signals were amplified and filtered at 1–1000 Hz. Ag/AgCl surface electrodes were attached to the belly of each muscle after cleaning and gentle abrasion of the skin. In the stepping task, the ground reaction forces and the COP during step executions were additionally recorded using a force plate (Tec Gihan, Kyoto, Japan). All signals (EEG, EOG, EMG, and ground reaction forces) were recorded at a sampling rate of 1000 Hz. The generation of visual imperative stimuli and the signal acquisitions were performed using a customized LabVIEW program (National Instruments, Austin, TX, USA).

### *Data analysis*

The offline data analysis was performed in Matlab (MathWorks, Natick, MA, USA) using customized scripts. To determine the TA EMG onset for the two tasks, we initially band-pass filtered the EMG signals obtained from the bilateral TAs with a fourth-order zero phase lag Butterworth filter with cut-off frequencies of 50–250 Hz. The TA EMG onsets were defined as the time at which the EMG amplitude was above three SD for at least 5 ms from the mean value calculated over a 500-ms pre-stimulus interval. The validity of the onset detection was additionally verified visually and adjusted manually when necessary. For the stepping task, given that the bilateral TAs co-activated when initiating the APA (Assaiante et al. 2000; Mickelborough et al. 2004; Delval et al. 2012) and that we had also confirmed that the left and right TA EMG onsets were not different ($p > 0.05$), the shorter latency was chosen as the trial onset (Lin and Yang 2011). For the dorsiflexion task, the trial onset was determined to be the latency of initial TA EMG activation of either left or right foot.

For the stepping task, the COP data recorded from the force plate were low-pass filtered at 50 Hz using a fourth-order zero phase lag Butterworth filter and were baseline-corrected with respect to a 500-ms pre-stimulus interval. In order to differentiate the APA initiation from mere oscillation of COP, its onset was defined using the COP movement speed (Delval et al. 2012). A threshold was set as follows: the COP speed > 100 mm/s for at least 3 ms. The APA errors were identified by the mediolateral deviation of COP toward the stance leg for at least 4 mm (Fig. 2) (Watanabe et al. 2015). For the dorsiflexion task, errors were identified as the initial TA EMG activation of the incorrect foot.

The obtained EEG signals were band-pass filtered at 1–15 Hz using a fourth-order zero phase lag Butterworth filter and segmented into epochs time-locked to the EMG onset. The frequency of the high-pass filter was chosen based on previous studies (Masaki et al. 2012; Grutzmann et al. 2014). They were further baseline-corrected with respect to a 100-ms pre-response interval. Prior to averaging the epochs, we excluded those contaminated with artifacts such as eye movements. The EEG signals were then averaged separately for correct and incorrect trials in each task, in order to evaluate the CRN and ERN. The CRN and ERN amplitudes were defined as peak-to-peak differences of the most negative peak found over the period of a 250-ms post-response interval and the positive peak preceding it.

### *Statistical analysis*

Before performing the statistical analysis, trials with onsets faster than 100 ms, trials with complete stepping errors in the stepping task, and trials with incorrect TA

EMG activity that appeared shortly after the correct TA EMG activity in the dorsiflexion task, were removed (5.9%). We also combined the left- and right-leg response data for each subject. Due to a high number of eye movement artifacts, three subjects were excluded from the statistical analysis of the ERP waveforms.

The error rates and TA EMG onsets on correct response trials were subjected to a two-factor repeated-measure analysis of variance (ANOVA) with the task types (stepping/dorsiflexion) and conditions (congruent/incongruent) as within-subject factors. The COP onsets on correct response trials were compared using a paired *t*-test. The ERP waveforms were subjected to a three-factor repeated-measure ANOVA with the task types, the response type (error/non-error), and electrode (Fz, FCz, or Cz) as within-subject factors. The degrees of freedom of *F* ratios were adjusted with a Greenhouse–Geisser correction when the sphericity assumption was violated. Post-hoc comparisons were performed with the Bonferroni test in case of significant main effects or interactions. Additionally, we examined the association between the interference effect, computed from the error rates of congruent and incongruent conditions, and the amplitude of ERP waveforms, using a Pearson’s correlation coefficient. Furthermore, the motor time (time from TA EMG onset to COP onset) of the congruent condition was compared with that of the incongruent condition using a paired *t*-test, in order to examine the effect of the interference on the motor time. Finally, to examine if a learning or fatigue effect existed, we compared, using a paired *t*-test, the mean error rates and reaction onsets of trials (congruent and incongruent trials combined) in the first block with those in the last block for the stepping task. We used SPSS (IBM, Armonk, NY, USA) for all statistical analyses with a significance level of 0.05.

## Results

### *Error rates*

Figure 3 shows the mean error rates of congruent and incongruent conditions for each task. The mean error rate (mean ± SE) in congruent trials was 10.2 ± 1.8% for the stepping task and 4.6 ± 1.5% for the dorsiflexion task. The mean error rate (mean ± SE) in incongruent trials was 74.6 ± 3.5% for the stepping task and 44.8 ± 6.9% for the dorsiflexion task. A two-factor ANOVA revealed the main effects of task ($F_{(1,11)} = 27.46$, $p < 0.001$) and condition ($F_{(1,11)} = 150.15$, $p < 0.001$). The interaction between task and condition was also significant ($F_{(1,11)} = 18.11$, $p = 0.001$), which was due to the finding that the difference in error rates between the congruent and incongruent conditions was greater for the stepping task than the dorsiflexion task. Post-hoc analysis indicated that the error rate was significantly higher in the incongruent conditions ($p < 0.001$). In addition, there was no significant difference in the error rate between the first and last blocks of the stepping task ($p = 0.44$), indicating that there was no learning effect as the blocks progressed.

### *Reaction onsets*

Figure 4 shows the mean reaction onsets of correct response trials. The TA EMG onsets of the congruent and incongruent conditions in each task, as well as the COP onsets in the stepping task, are presented. A two-factor ANOVA for the TA EMG onsets revealed the main effects of task ($F_{(1,11)} = 94.86$, $p < 0.001$) and condition ($F_{(1,11)} = 57.19$, $p < 0.001$) as well as their interaction ($F_{(1,11)} = 57.11$, $p < 0.001$). A simple effects analysis indicated that the TA EMG onsets of the incongruent condition were significantly longer than those of the congruent condition ($p < 0.001$), and that TA EMG onsets of the stepping task were significantly longer than those of the dorsiflexion task ($p < 0.001$). The revealed interaction can be attributed to the magnitude of difference in the TA EMG onsets between the congruent and incongruent conditions. The COP onsets of the incongruent condition were found to be significantly longer than those of the congruent condition ($p < 0.001$). Furthermore, the motor time was significantly longer in the incongruent than congruent condition, indicating some additional processing occurred between the TA EMG and COP onsets in the incongruent condition for the stepping task. In addition, there was no significant difference in the reaction onsets between the first and last blocks of the stepping task ($p = 0.74$), indicating that there was no fatigue effect as the blocks progressed.

### *Event-related potential data*

Figure 5 depicts the response-locked grand-average ERP waveforms for error and correct trials at Fz, FCz, and Cz. The response-related negativity (i.e., ERN/CRN) was evident as a sharp negative deflection, peaking around 150 ms after the EMG response. A three-factor ANOVA revealed the main effects of task (Fz: $F_{(1,8)} = 11.40$, $p = 0.010$), error ($F_{(1,8)} = 7.52$, $p = 0.025$), and their interaction ($F_{(1,8)} = 13.37$, $p = 0.006$). A simple effects analysis indicated that both ERN ($p = 0.027$) and CRN ($p = 0.003$) were significantly larger in the stepping task than the dorsiflexion task. Furthermore, the ERN was significantly larger than CRN in the dorsiflexion task ($p < 0.001$) but not in the stepping task ($p = 0.925$), explaining the nature of the interaction found between the task and error. Post-hoc analysis confirmed this and indicated statistical significance as follows: Fz ($p = 0.001$), FCz ($p < 0.001$), and Cz ($p = 0.001$). In addition, the interference effect correlated with the amplitude of the ERN (r

= 0.70, *p* = 0.037) and the CRN (r = 0.72, *p* = 0.029) at Fz in the stepping task but not in the dorsiflexion task.

## Discussion

The present study investigated information processing and performance monitoring during a choice stepping reaction time task and a CRT task with ankle dorsiflexion responses, using a Simon task. Consistent with previous studies (e.g., Masaki et al. 2012), the error rate was higher in the incongruent condition, and the onset time of the correct response was shorter in the congruent condition for both tasks, indicating the presence of interference effects. More importantly, we were interested in clarifying the difference in the processes of response conflict resolution between the stepping reaction and the limb reaction performed in a seated position. We evaluated the response-related negativities that can be observed just after correct and incorrect responses, and revealed that the amplitude of ERN was larger than that of CRN in the dorsiflexion task whereas the amplitudes of ERN and CRN were not different in the stepping task, contrary to our hypothesis. Furthermore, the amplitude of the ERN was larger during the stepping task than the dorsiflexion task. These findings indicate that a strategy implemented to resolve response conflict during a choice stepping reaction would be distinct from a strategy implemented during a CRT task with limb responses, and that correcting the APA error would be cognitively more difficult than correcting an error committed in a seated position.

There has been considerable debate about the functional implication of CRN. Our results show that the CRN amplitude was smaller than the ERN amplitude in the dorsiflexion task, which is consistent with previous studies applying SRC tasks with upper- and lower-limb responses (e.g., Holroyd et al. 1998; Hajcak et al. 2005;

Masaki et al. 2012). On the other hand, the amplitudes of CRN and ERN were similar in size for the stepping task. It has been reported that the CRN amplitude increases when there is response uncertainty (Scheffers and Coles 2000; Pailing and Segalowitz 2004). This explanation, however, seems unlikely since stimulus degradation or the dual attention procedure employed in previous studies to alter response certainty was not used in the present study. Another factor that could contribute to the CRN amplitude is a response strategy employed by individuals. The CRN amplitude relates to the temporal allocation of cognitive control (Luu et al. 2000; Bonnefond et al. 2011; Grutzmann et al. 2014). In particular, Grutzmann et al. (2014) manipulated the frequency of congruent and incongruent trials, latently having the subjects allocate their cognitive control to either pre-response or post-response, and suggested that enhanced cognitive control of post-response conflict increases the CRN amplitude, whereas that of pre-response stimulus conflict decreases it. In this study, the CRN amplitude became larger and similar to the ERN amplitude in the stepping task without a conflict frequency manipulation. Therefore, a response strategy that places more emphasis on the post-response conflict resolution may be chosen and judged to be most suitable to comply with a choice stepping reaction task, since APA errors, even if committed, can be corrected in the period between reaction and foot lift without making a full stepping error. This assumption is further supported by our behavioral data of the motor time. It has been shown that motor time is not influenced by the interference induced by the Simon task (Hasbroucq et al. 1999; Burle et al. 2002), and thus it should be the same duration for the congruent and incongruent conditions. In the stepping task, however, motor time was longer in the incongruent condition than the congruent condition, indicating the presence of cognitively guided adjustment after initiating the APA but before reaching the level of APA error.

Furthermore, there was a significant correlation between the CRN amplitude and the interference effect in the stepping task, which implies that the error rate increases as one induces more cognitive effort to the post-response conflict and less cognitive effort to the stimulus conflict. In addition, APAs can be prepared or preprogrammed before the presentation of an imperative stimulus during a stepping task (MacKinnon et al. 2007; Delval et al. 2012; Watanabe et al. in press), potentially indicating that individuals may start a stepping sequence with a prepared APA and adjust it when it is incorrect; inadequate adjustments would result in APA errors. Accordingly, post-response cognitive control of incorrectly prepared APAs conceivably contributed to the increased CRN amplitude.

An additional explanation for the similar-sized ERN and CRN amplitudes involves the neural processes underlying those two negativities. Although it has long been proposed that ERN and CRN share a single functional process that is activated more after an error response than a correct response (Vidal et al. 2000; Vidal et al. 2003), emerging evidence suggests that they reflect two different processes, one for general performance monitoring, and the other for an error signal (Falkenstein et al. 2000; Luu and Tucker 2001; Endrass et al. 2012). The finding that those two negativities are affected differently by several pathological conditions as well as aging further supports the latter view (e.g, Araki et al. 2013; Carrasco et al. 2013). In line with this perspective, Schreiber et al. (2011) revealed similar-sized ERN and CRN amplitudes in the elderly and indicated that the elderly participants might have increased general performance monitoring and decreased error-specific monitoring. In the present study, it is plausible that the general performance monitoring of actual and required responses has been emphasized in the stepping task, and the error-specific monitoring has mainly been active in the dorsiflexion task. This notion is further supported by the finding of a significant correlation between the ERN/CRN amplitude and the interference effect only in the stepping task, assumedly indicating that the cognitive resource was allocated primarily to carefully monitor the response in the stepping task and to detect errors in the dorsiflexion task.

Along the same line of discussion, types of error may have contributed to the current finding of similar-sized ERN and CRN amplitudes. APA errors are brief, covert, and are likely corrected by initiating a step with the appropriate leg as mentioned above. In the current study, only a few complete stepping errors occurred and were thus excluded from the data analysis. As aware errors are reported to produce larger ERN amplitudes than non-aware errors do (Wessel et al. 2011), although the findings are inconsistent (Hughes and Yeung 2011), ERN amplitude may have become smaller because APA errors were not recognized as definite errors in some trials. The greater ERN amplitude than CRN amplitude might have been observed if EEG signals from trials with complete stepping errors, which are highly unlikely to occur in young individuals, were averaged.

In addition to factors discussed already, there is a possibility that cortical activities related to stepping movement itself have influenced the ERN and CRN. During movement, movement-related potentials (MRPs), which are the averaged ERP components triggered by movement onset, can be recorded (Shibasaki and Hallett 2006). MRPs are reported to reflect movement preparation, execution, and kinesthetic feedback (Shibasaki et al. 1981), and have been observed in various movements, including stepping (do Nascimento et al. 2005; Varghese et al. 2016) and dorsiflexion (Shibasaki et al. 1981). In the present study, as MRPs can be larger during standing than sitting (Yoshida et al. 2008), the MRP amplitude might have been substantially larger in the stepping task than the dorsiflexion task, potentially overlapping and masking the ERN and CRN. There might have been greater cortical activity associated with the movement than error processing or performance monitoring during the stepping task.

It may be argued that the shorter reaction onset and higher error rate in the stepping task than the dorsiflexion task were simply the consequence of speed-accuracy trade-off. Although we did not instruct the subjects to focus on speed, they may have unintentionally selected such a strategy in the stepping task. Previous ERP studies have, however, demonstrated smaller ERNs when the emphasis is on speed over accuracy (Gehring et al. 1993; Arbel and Donchin 2009), which contradicts our ERN results, as described below. Therefore, in accordance with the argument above, we suggest that both speed and accuracy are emphasized during a choice stepping reaction task. The APA appears to be monitored attentively and carefully throughout the APA duration in order to avoid APA errors as well as complete stepping errors, signifying the cognitive control of post-response conflict. The subjects possibly selected this strategy to comply with the instruction "as quickly and accurately as possible."

In addition to the similar-sized ERN and CRN amplitudes, the ERN amplitude was larger in the stepping task than in the dorsiflexion task. One explanation could be that the MRP, which might have increased in amplitude due the standing position, potentially masked the ERN in the stepping task, as noted previously. The other explanation is the heightened response force and post-response cognitive load. It has been reported that the greater the strength of response force, the higher the amplitude of the ERN (de Bruijn et al. 2003; Armbrecht et al. 2013). Since the stepping task involves whole-body movements and thus requires greater action modifications during the post-response conflict process in order to correct APA errors, we suggest that higher erroneous response force and its associated cognitive load have contributed to the greater amplitude of the ERN. In accordance with this view, the amount of interference induced by the SRC paradigms has been shown to be associated with the amplitude of the ERN (Masaki and Segalowitz 2004; Masaki et al. 2012). Even though we applied the same SRC paradigms to both tasks, it might have been more difficult to correct the induced interference, thus resulting in more errors in the stepping task than the dorsiflexion task, as the behavioral data of the error rates confirm (Fig. 3). The generation of APA is also known to involve the basal ganglia, premotor cortex, supplementary motor area, and motor cortex (Massion 1992; Chang et al. 2010), and its quality declines as people age (Woollacott and Manchester 1993; Kanekar and Aruin 2014), suggesting that control of APA is quite complicated. Hence, the post-response conflict resolution required during a choice stepping reaction task seems to be a challenging task.

The ability to initiate a volitional step quickly and appropriately in response to an environmental stimulus is necessary for maintaining balance and avoiding falls. APA errors can delay volitional step execution time, and have been reported to be associated with fall risks in the elderly (Ejupi et al. 2014; Schoene et al. 2014; Delbaere et al. 2015). It has also been suggested that APA errors are related to inhibitory function (Cohen et al. 2011; Sparto et al. 2013; Uemura et al. 2013; Watanabe et al. 2015). The present study suggests that there is a tendency to solve response conflict after initiating an APA but before committing a complete stepping error; APA errors occur when an inappropriately initiated APA could not be inhibited. These indications suggest that more inhibitory control is implemented after rather than before responding to a stimulus during a choice stepping reaction. Older individuals with a higher risk of falls may therefore be more likely to react impulsively to a stimulus and have less capacity to inhibit the inappropriately initiated APA, resulting in multiple APAs (i.e., APA errors). Not only inhibitory function but also impulsivity can be an important factor for preventative interventions (Morales-Vives and Vigil-Colet 2012). However, previous studies with experiments conducted in a seated position have shown that older individuals prefer accuracy over speed with longer RTs and smaller error rates (e.g., Smith and Brewer 1995; Sharp et al. 2006). Therefore, evaluating the strategy selection as well as the cortical processing during a choice stepping reaction task in the elderly may be interesting and could be a subject for a future study.

Despite the importance of the current findings that have extended knowledge of the cognitive activities that occur during a choice stepping reaction task, there were several limitations. First, the cognitive load might have been enhanced in the stepping task by the instruction to balance the weight evenly on both legs before initiating a step. Even though the potential effects of this on our results should be acknowledged, weight distribution on one side had to be avoided to accurately measure the APA initiation (Shinya et al. 2009). Secondly, as we were unable to locate neural sources, we cannot comment on the neural origin of the negative ERP component identified in the present study. Although the exact origins of ERN and CRN are still under investigation, identifying the neural sources could have strengthened our discussion. Lastly, this study was conducted in younger individuals, and the effect in older individuals at risk of falling is unknown, requiring further investigation.

To our knowledge, this was the first study investigating the cortical activities during a choice stepping reaction task. Specifically, we examined two ERP components, namely the ERN and CRN, in a choice stepping reaction time task and a CRT task involving ankle dorsiflexion responses, and revealed that the ERN and CRN were similar in size in the stepping task while the ERN amplitude was larger than the CRN amplitude in the dorsiflexion task. Furthermore, the amplitude of the ERN in the stepping task was larger than that in the dorsiflexion task. Although it should be noted that cortical activity associated with motor aspect of the tasks and the task instruction potentially influenced the results, these findings might indicate that a strategy emphasizing post-response conflict resolution and general performance monitoring of responses is primarily employed during a choice stepping reaction task. It is also suggested that extensive physical and cognitive load is required to control and modify APAs. The current findings advance our understanding of response conflict resolution during choice stepping reaction tasks.

## Conflict of interest

The authors declare that they have no conflict of interest.

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## Figure Captions

**Fig. 1** Experimental design for the Simon task. The visual imperative stimulus was presented for 500 ms with a 6.5-s inter-trial interval. The Simon task consisted of congruent and incongruent conditions. The subject responded to one of four stimuli presented on the right side

**Fig. 2** Representative step execution data for trials with correct (above) and incorrect (below) responses. The correct-response trial shows one single anticipatory postural adjustment (APA), whereas the incorrect-response trial shows two APAs (i.e., APA error). Time 0 indicates the presentation of a visual imperative stimulus and the arrow denotes the APA onset

**Fig. 3** Mean error rate for stepping and dorsiflexion tasks. The gray column represents congruent trials and the black column represents incongruent trials. Error bars are standard error of the mean

**Fig. 4** Mean reaction onset on correct trials for stepping (left) and dorsiflexion tasks (right). The solid line represents the mean tibialis anterior (TA) electromyographic (EMG) activity onset, and the dashed line represents the initiation onset of center of pressure (COP). Error bars are standard error of the mean

**Fig. 5** Representative data of response-locked event-related brain potential (ERP) waveforms obtained at Fz, FCz, and Cz for correct and incorrect responses during stepping (left column) and dorsiflexion tasks (right column). Each line represents as follows: the thick solid line for correct APA trial, the thick dashed line for incorrect APA trial, the thin solid line for correct dorsiflexion trial, and the thin dashed line for incorrect dorsiflexion trial