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The role of an auditory cue in generating anticipatory postural adjustments in response to an external perturbation

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Abstract

Anticipatory postural adjustments (APAs) are usually generated to minimize the potential postural disturbance induced by predictable external perturbations. Visual information about a perturbation is important for the generation of APAs but whether people can rely on auditory information to generate APAs is unknown. The aim of this study was to investigate the role of an auditory cue in generating APAs when visual information is not available. Fifteen young adults participated in the study when they received external perturbations with visual information but no auditory information available, without neither visual nor auditory information, with both visual and auditory information available, and with only auditory information available. Electromyography (EMG) activities of eight leg and trunk muscles and displacements of the center-of-pressure (COP) were recorded and analyzed during the anticipatory and compensatory (CPAs) phases. Outcome measures included the latencies and integrals of muscle activities, COP displacements, and indices of co-contraction and reciprocal activation of muscles. The results showed that after a short training, participants were able to rely only on the auditory cue to generate APAs comparable to that when the visual information was available. In addition, a training effect was found such that the participants demonstrated stronger APAs and less demands for CPAs through the training trials. The outcome provides a foundation for future studies focusing on the utilization of auditory cues for postural control in older adults and individuals who have vision deficit.

Key words: auditory cue, external perturbation, balance control, anticipatory postural adjustments

1. Introduction

While standing or walking, people frequently experience external perturbations (i.e. a hit or a bump) that create dynamic forces and disturb their balance. To maintain balance, the central nervous system (CNS) uses two strategies to regulate the activities of the trunk and leg muscles: anticipatory postural adjustments (APA) and compensatory postural adjustments (CPA). APAs are feed-forward postural reactions that occur before the perturbation impact and they are generated to control the position of the center-of-mass (COM) and hence to minimize the potential postural disturbance (Bouisset and Zattara 1987; Massion 1992; Aruin et al. 2001). On the other hand, CPAs serve as corrective measures after the actual perturbation impact to restore the position of the COM (Nashner and Cordo 1981; Alexandrov et al. 2005). If APAs are generated timely and appropriately, it could help to reduce the instability caused by the external perturbation and consequentially reduce the need for large CPAs after the perturbation impact (Santos et al. 2010a; Santos et al. 2010b).

APAs are usually observed as the activation or inhibition of the trunk and leg muscles and a slight posterior shift of COP position when people see the external perturbation coming from the front but before the physical impact happens (Massion 1992). However, the generation of APAs majorly relies on the availability and accuracy of the visual information. When the visual information becomes unavailable and the perturbation is unexpected (such as being hit in a crowded place in real life scenery or being asked to close the eyes in a lab setting), CPAs are the only mechanism used by the CNS to restore balance (Santos et al. 2010a; Piscitelli et al. 2017). Furthermore, it was shown that when the same magnitude of external perturbation was applied to a body, larger EMG responses were required and larger COP peak displacement was observed in the CPAs phase when the eyes were closed and therefore the perturbation was unpredictable (Santos et al. 2010a; Santos et al. 2010b; Zhang et al. 2019). Additionally, when the visual information about the forthcoming perturbation was manipulated such that it became less accurate, the APAs appeared to be less efficient with a smaller magnitude and/or delayed muscle latencies (Aruin et al. 2001; Mohapatra et al. 2012; Mohapatra and Aruin 2013).

To maintain balance, the CNS employs two patterns of activation of trunk and leg muscles: co-contraction and reciprocal activation (Mochizuki et al. 2004). Co-contraction of the muscles involves simultaneous activation of agonist and antagonist muscles which increases the joint stiffness and consequentially the level of joint stability. Co-contraction of muscles is commonly used by older adults in response to an external perturbation (Lee et al. 2015) and is associated with increased energy expenditure. Reciprocal activation of the muscles involves activation of agonist muscle followed by activation of the antagonist muscle and is a more efficient strategy to maintain an upright posture (van der Fits et al. 1998). In previous studies involving predictable perturbations, a reciprocal activation of muscles was dominant in the APAs phase (Chen et al. 2017) and could still be observed in the CPAs phase (Santos et al. 2010a). Specifically, when seeing the perturbation coming from the front, participants activated the ventral muscles and inhibited the dorsal muscles during the APAs phase (Chen et al. 2017). On the other hand, when participants closed their eyes and the perturbation became unpredictable, no APAs were observed and a larger magnitude of co-

contraction muscle activities were required during the CPAs phase to maintain balance (Santos et al. 2010a).

People learn to generate and scale the magnitude of the muscle responses to the expected perturbation through previous experiences (Bastian 2006) and such experiences are gained majorly based on visual information. A previous study investigated the anticipatory forearm muscle activities under the condition that the visual information was excluded but an auditory cue was given when participants were catching a falling ball (Lacquaniti and Maioli 1987). It was reported that seated participants were unable to generate consistent anticipatory activities because the impact time was unpredictable using that novel auditory cue (Lacquaniti and Maioli 1987). On the other hand, it was demonstrated that while seated, people were able to acquire and optimize the APAs of the postural forearm after 40-60 trials for a bimanual task, and this interlimb coordination was related to a central timing signal but not related to the force of the voluntary movement of the other forearm (Paulignan et al. 1989; Massion et al. 1999). Furthermore, when experiencing a postural perturbation while standing, people were able to enhance their APAs after several trials of exposure if the magnitude and timing of the perturbation were consistent (Aruin et al. 2015b; Arghavani et al. 2019). Therefore, if people were given repetitive exposures allowing to build a connection between the timing of an auditory cue and postural perturbations, they might be able to rely on this auditory signal to generate APAs. Older adults (Kanekar and Aruin 2014) and people with visual impairment (Alghadir et al. 2019) have diminished postural control and also diminished APAs in the events of postural perturbations. Using auditory information could be beneficial to these populations. However, to our knowledge, the feasibility and effectiveness of using an auditory cue to generate APAs in standing after a short period of training has never been examined in any population. The purpose of this study was to determine the role of an auditory cue in generating APAs in response to an external perturbation in young adults. The hypothesis was that with training, young adults would be able to make connections between the auditory cue and the moment of the perturbation and generate APAs relying only on the auditory cue.

2. Materials and Methods

2.1 Subjects

Fifteen healthy young adults (8M/7F) between the ages of 18 to 35 years old were recruited for the study. The exclusion criterion was having any injuries to the musculoskeletal system within the past six months. The mean (SD) of the participants' age, height, and weight were 29.1 (4.8) years, 168.3 (7.6) cm, and 62.8 (12.1) kg respectively. The study was approved by the hosting university's institutional review board and all the participants provided written informed consents before the data collection.

2.2 Procedure

The participants were instructed to stand in the middle of a force plate (AMTI, Watertown, MA, USA) and be prepared for an external perturbation provided by an aluminum pendulum attached to the ceiling (Fig.1). The pendulum was initially positioned at an angle of 30 degrees to the vertical at a distance of 0.6m from the body, and it was released by the same research assistant. An additional load equaling to 5% of each participant's body weight was attached at the end of pendulum (Chen et al.

2017). There were two wooden boards covered with foam pads extended from the end of the pendulum. The settings were adjusted for each participant so that these two foam boards would hit the front side of both shoulders simultaneously. The participants were asked to stand barefoot with feet shoulder width apart. The headphones were worn by the participants throughout the whole experiment to block the noise caused by the release of the pendulum. A removable (30x30cm) screen (white foam board) was placed in front of the participants at eye level that could block the sighting of the upcoming pendulum but did not affect peripheral vision. Participants were asked to maintain an erect posture with their upper extremities along the body (with the palms towards the body). Then, after a “ready” signal, a research assistant released the pendulum with a 1-10 seconds delay so that the participant could not predict the timing of the release based on experience with previous trials. Prior to the main experiment, participants were provided with two to three practice trials of receiving the pendulum perturbation with full vision. The experiment consisted of 5 conditions implemented in the following order: baseline while vision was available (*BL_V* condition) for 5 trials, baseline while vision was not available (*BL_NV* condition) for 5 trials, *Acclimation* condition for 10 trials, training (*Tr*) condition for 50 trials, and one *Catch* trial (Fig.1).

< Fig. 1 >

Firstly, for the *BL_V* condition, participants received the pendulum perturbation with full visual information available. Then for the *BL_NV* condition, participants received the pendulum perturbation with the white screen blocking the vision. For the

Acclimation condition, participants received the pendulum impact with both full visual information (vision was not blocked) and an auditory cue. The timing between the release of the pendulum and the physical contact of the pendulum was 0.5 second for all the trials. The auditory cue (a beep) indicating the moment of the pendulum release was delivered to subjects via the headphones at a consistent timing of 0.5 second before the physical contact of the pendulum so that participants could use the auditory signal to predict the timing of the pendulum contact. A magnetic switch (Absolute Automation, Casco, MI, USA) was attached to the frame holding the pendulum and it sent the signal to initiate the beep (1 kHz, 0.25s duration) triggered by the pendulum release. Then, during the *Tr* condition, participants received the pendulum perturbations with their vision blocked, but they still received the same auditory cue at the time of the pendulum release. Finally, one *Catch* trial was performed when the participants heard the auditory cue, but the pendulum was stopped by a researcher before the impact. Rest was provided to the participants when needed to avoid fatigue.

An accelerometer (PCB Piezotronics, Inc., Depew, NY) was attached to the end of the pendulum to identify the moment of its impact with the participants' shoulders (T0). An electromyographic (EMG) system (Myopac, RUN Technologies, USA) was used to record the leg and trunk muscle activities bilaterally from tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), biceps femoris (BF), gluteus medius (GM), external obliques (EO), rectus abdominus (RA), and erector spinae (ES). The skin area was cleaned with alcohol wipes. The disposable surface electrodes (Red Dot, 3M, St. Paul, MN, USA) were attached in pairs with a center-to-center distance of 25mm and the placements were based on the recommendations reported in the literature (Zipp

1982). The ground electrode was placed on the right lateral malleolus. A customized LabView 8.6.1 software (National Instruments, Austin, TX) was used to collect the data from the switch, accelerometer, force plate, and the EMG system at a frequency of 1000 Hz, as well as sending a beeping sound at the time of pendulum release.

2.3 Data analysis

A custom-written MATLAB program (Mathworks, Natick, MA, USA) was used for data processing. The time of the pendulum impact (T0) was defined using the accelerometer data as the first time point when the acceleration exceeded 5% of its peak value (Aruin et al. 2015a). The force plate and the EMG signals were aligned according to T0.

The EMG signals were filtered with a fourth order high-pass Butterworth filter with a cut-off frequency of 30Hz (Drake and Callaghan 2006). Then the EMG signals were full-wave rectified and linear envelopes were created with a 20Hz low-pass Butterworth filter. The baseline of muscle activity was calculated using the mean value between -500ms and -450ms (Aruin et al. 2001; Santos et al. 2010a). The muscle latency was defined as the first time point within a window of 50ms that the EMG amplitude was consistently greater (activation) or smaller (inhibition) than its baseline value ± 2SD. All the latency detections were checked visually by an experienced researcher for the accuracy. Integrals of the EMG activities (IntEMGi) were calculated during two 300ms windows: (1) anticipatory postural adjustments (APA), from -250ms to +49ms; and (2) compensatory postural adjustments (CPA), from +50ms to +350ms (Santos et al. 2010a). Then each integral was further corrected by the integral of corresponding baseline activity. Furthermore, EMG integrals were normalized by the absolute maximum EMG integral value across all conditions for each muscle and participant respectively (Lee 2019):

NormEMG_APAi = $\left(\int_{-250}^{+49} EMGi - 6\int_{-500}^{-450} EMGi\right) \Big/ IntEMGimax$

NormEMG_CPAi = $\left(\int_{+50}^{+350} EMGi - 6\int_{-500}^{-450} EMGi\right) \Big/ IntEMGimax$

where i stands for each of the eight muscles tested.

As a result, all the NormEMG integral values were within -1 to +1. The negative values represented the inhibition of muscle activities with respect to the background activity. In addition, to evaluate the co-contraction and reciprocal activation of the muscle activities, a whole body model was used and the C and R indices were calculated for the APA and CPA phases respectively using the equation below (Chen et al. 2017):

C = $\int NormEMG\_ventral + \int NormEMG\_dorsal$,

R = $\int NormEMG\_ventral - \int NormEMG\_dorsal$

where the ventral muscles include TA, RF, and RA, and dorsal muscles include MG, BF, and ES.

Force plate data were filtered with a fourth order low-pass Butterworth filter with a cut-off frequency of 40Hz (Kanekar and Aruin 2014). Then, the center-of-pressure (COP) time series were derived from the force plate data and its displacements in the anterior-posterior (AP) direction were used for further analysis. The baseline of COP-AP was calculated using the mean value from -500ms to -450ms and the baseline was subtracted from the COP-AP time series. The COP-AP displacement at T0 and its peak value after T0 were identified.

Since the pendulum hit both the participants' shoulders, the perturbation can be considered symmetrical. Therefore, only the EMG parameters of the right side were used in the analysis. For each participant, data were then organized into 5-trial blocks and the average of the 5 trials was used for further analysis. Specifically, there was 1 block for *BL_V* condition, 1 block for *BL_NV* condition, 2 blocks for *Acclimation* condition, and 10 blocks for *Tr* condition. There was 1 single trial for the *Catch* condition. For the *Catch* condition, only the outcomes during the APA phase (muscles latencies, integrals during APA, and COP at T0) were used for further analysis.

2.4 Statistical analysis

A series of one-way repeated measure ANOVAs were conducted on the dependent variables (EMG latency, normalized EMG integrals at two epochs for each muscle, C and R indices, COP at T0, and COP peak) for the *BL_V* and 2 blocks of *Acclimation* conditions. No differences were found in any of the variables and the *Acclimation* condition was excluded from further analysis. A series of one-way repeated measure ANOVAs were conducted on the abovementioned dependent variables to test the condition effect among *BL_V*, *BL_NV*, *Tr_1* through *Tr_10* and *Catch* conditions. Post-hoc pairwise comparisons with Bonferroni adjustments were conducted when necessary. Skewness and kurtosis were used to assess the normality of the data and a log transformation of the data was applied when necessary. Statistical significance was set at α=0.05.

3. Results

3.1 EMG profiles

The EMG traces obtained from the two lower leg muscles (TA and MG) of a representative participant during different conditions are shown in Fig.2. An activation of the TA and inhibition of MG before T0 could be observed in *BL_V* condition when visual information was available. No APAs were observed in the *BL_NV* condition when neither visual nor auditory information was available. However, later during the Training trials (*Tr_6* and *Tr_10* in Fig.2) when the auditory cue was provided, strong anticipatory activity of muscles was observed.

< Fig. 2 >

3.2 EMG latency

For most muscles tested, the general pattern in *BL_V* condition was that the ventral muscles (TA, RF, and RA) displayed increased activation, while the dorsal muscles (MG, BF, and ES) displayed an inhibition of muscle activities prior to the T0. In the *BL_NV* condition, the latencies of muscles were detected after T0, or slightly before T0. Throughout the *Training* conditions, the latencies of the muscles gradually became seen earlier and reached the same level as the *BL_V* (Table 1). Statistical analysis showed that there were significant differences among conditions for the latencies of TA ($F(12,167)=6.38$, $p<0.001$), MG ($F(12,150)=13.61$, $p<0.001$), RF ($F(12,168)=9.39$, $p<0.001$), EO ($F(12,166)=6.94$, $p<0.001$), and RA ($F(12,161)=4.19$, $p<0.001$). Post-hoc analysis revealed that latencies in *BL_NV* condition were later than in all the other conditions in all the above-mentioned muscles (all $p<0.05$). The latencies in *BL_V* were seen earlier than in *Tr_1* in TA and MG, and earlier than in *Tr_1* through *Tr_4* in RF (all $p<0.05$). Additionally, the latencies during *Tr_1* were significantly later than during*Tr_6* through *Tr_10* and *Catch* in TA and MG, later than in *Tr_5* through *Tr_10* and *Catch* in RF, and later than in *Tr_10* and *Catch* conditions in EO and RA. The latencies during *Tr_2* and *Tr_3* were also significantly later than during *Tr_10* and *Catch* in TA, MG, and EO (all $p<0.05$). No significant differences in the latencies were found among *Tr_6* through *Tr_10* for any muscles.

Even though all the participants demonstrated some level of inhibition in the BF and ES muscles prior to T0, the latency of that inhibition activity could only be detected in less than half of the participants. In those participants, the latencies of BF and ES muscles appeared similar among all the conditions except for *BL_NV*, and the latencies in *BL_NV* condition were later than that in all the other conditions. Due to the amount of missing data, statistical analysis on the latencies of BF and ES were not conducted, but the data are presented in Table 1.

< Table 1 >

3.3 EMG integrals

A larger activity during APA phase and a relatively smaller activity during CPA phase was observed in the *BL_V* compared to *BL_NV* condition. Throughout the *Training* condition, the general trend was an increase of integrals of APA activities and a decrease of integrals of CPA activities for all the muscles examined (Fig.3).

For the EMG integrals during the APA phase, statistical analysis revealed significant differences among conditions for TA ($F(12,168)=2.91$, $p=0.001$), MG ($F(12,168)=2.13$, $p=0.017$), RF ($F(12,168)=4.26$, $p<0.001$), and EO ($F(12,168)=2.97$, $p<0.001$). Post-hoc analysis showed that the APA integrals during *BL_NV* condition were significantly smaller than those in all the other conditions except *Tr_1* for the muscles mentioned above (all $p<0.05$). Additionally, the EMG integrals during *Tr_1* were significantly smaller than that during *Tr_10* for TA, RF, and EO. The EMG integrals during *Tr_10* were also significantly larger than that during *Tr_2* to *Tr_4* for RF, and larger than that during *Tr_3* and *Tr_5* for EO (all $p<0.05$).

For the EMG integrals during the CPA phase, statistical analysis showed significant differences among conditions for TA (F(11,154)=6.91, $p<0.001$), RF (F(11,154)=5.45, $p<0.001$), BF (F(11,154)=3.10, $p<0.00$), GM (F(11,154)=14.61, $p<0.001$), EO (F(11,154)=4.91, $p<0.001$), RA (F(11,154)=5.75, $p<0.001$), and ES (F(11,154)=7.75, $p<0.001$). Post hoc analysis revealed that CPA integrals for *BL_NV* condition were significantly larger than integrals for *Tr_2* through *Tr_10* for TA, RF, GM, EO, RA, and ES (all $p<0.05$). The CPA integrals for *BL_V* were significantly smaller than that in *Tr_1* for TA and RF (both $p<0.05$). Additionally, the CPA integrals during *Tr_1* were larger than *Tr_9* through *Tr_10* for all these muscles. The CPA integrals during *Tr_10* were smaller than *Tr_2* and *Tr_3* for TA, RF, and BF; and smaller than *Tr_3* and *Tr_5* for RA and ES (all $p<0.05$). No differences in the APA or CPA integrals were found among *Tr_6* through *Tr_10* for any muscles.

< Fig. 3 >

3.4 C and R indices

Generally, during the APA phase in all the conditions except *BL_NV*, R index was larger than C index; while during the CPA phase, C index was larger than R index (Fig.4). Statistical analysis revealed that there were significant differences among conditions for R index during the APA phase (F(12,168)=4.10, $p<0.001$) and C index during the CPA phase ($F(11,154)=12.65$, $p<0.001$). Post-hoc analysis showed that for the *BL_NV* condition, R_APA was smaller while C_CPA was larger than in all the other conditions (all $p<0.05$). *Tr_1* showed a smaller R_APA and a larger C_CPA than in *Tr_9* through *Tr_10*. Additionally, *Tr_10* showed a smaller C_CPA than in *Tr_1* through *Tr_5* (all $p<0.05$).

< Fig. 4 >

3.4 COP displacements

When the participants could see the forthcoming pendulum (*BL_V*), their COP moved posteriorly during the APA phase (prior to the perturbation impact). When the moment of the pendulum impact was unpredictable (*BL_NV*), the COP at T0 was close to 0, and the peak displacement during the CPA phase was larger. Overall, throughout the *Training* condition, there was a gradual increase of the posterior displacement of the COP at T0 during the APA phase and a decrease of peak displacement during the CPA phase (Fig.5a and 5b). Statistical analysis showed that there were significant differences among conditions for both COP at T0 ($F(12,168)=8.84$, $p<0.0001$) and peak displacement ($F(11,154)=4.13$, $p<0.0001$). Post hoc analysis revealed that for COP at T0, *BL_NV* displayed a significantly smaller posterior displacement than in all the other conditions except *Tr_1* (all $p<0.05$). Additionally, *Tr_1* had a significantly smaller COP posterior displacement than *BL_V*, *Tr_4* through *Tr_10*, and *Catch* conditions; and *Tr_10* showed a significantly larger posterior displacement than *Tr_1* through *Tr_4* (all $p<0.05$). For the COP peak displacement, *BL_NV* has the largest value and it was significantly larger than all the other conditions (all $p<0.05$). *BL_V* showed a smaller value than *Tr_2* and *Tr_3*; and *Tr_10* displayed a smaller value than *Tr_1* through *Tr_3* (all $p<0.05$).

< Fig. 5 >

4. Discussion

This study examined whether the APA associated with an external perturbation could be generated using an auditory cue only. The results demonstrated that with repetitive exposures to the perturbation, young adults were able to rely only on an auditory cue to generate adequate APAs that were comparable to that when visual information was available. As such, our hypothesis was supported.

4.1 Role of availability of visual or auditory information in postural control

The effect of availability of visual information in generating APAs has been explored in the literature (Aruin et al. 2001; Santos et al. 2010a; Santos et al. 2010b; Mohapatra et al. 2012; Zhang et al. 2019). In agreement with the previous studies, our results showed minimal change of muscles activities before the perturbation impact when the vision was obstructed and therefore the perturbation was unexpected. When an auditory cue was provided to the participants (especially during *Tr_6* through *Tr_10*), they showed anticipatory activation/inhibition of the trunk and leg muscles prior to the perturbation impact similarly as that when visual information was available. Furthermore, when either visual or auditory information was available, participants generally displayed earlier latencies for the leg muscles (between -250ms to -100ms) than the trunk muscles. The observation of such a distal to proximal pattern of APA generation is in line with the previous literature (Santos et al. 2010a).

Additionally, the existence of a relationship between the magnitude of APAs and CPAs for postural control and that the generation of strong APA can result in reduced requirements of muscle responses in the CPA phase has been described in the previous literature (Santos et al. 2010a; Santos et al. 2010b). In agreement with that, we also report larger EMG integrals during the APA phase and smaller integrals during the CPA phase when either visual (*BL_V*) or auditory (*Tr_1* through *Tr_10*) information was available, but smaller APA and larger CPA when the perturbation was unpredictable (*BL_NV*). Previous studies showed that when visual information about the upcoming perturbation was available, there was a backward displacement of the COP in preparation for the perturbation (Stapley et al. 1998; Santos et al. 2010b). Similar backward COP displacements were observed in the current study when the participants obtained information about the forthcoming perturbation using either visual information (*BL_V*) or an auditory cue (*Training* and *Catch* conditions). This initial posterior movement of the COP could create the momentum that assists the whole body to move forward in preparation for the upcoming perturbation (Santos et al. 2010b). The COP peak displacement reflected the body sway after the perturbation impact, and it was smaller in conditions with either visual or auditory information as compared to the unpredictable perturbation condition (*BL_NV*). These results suggest that young adults could use the auditory cue to control their postural stability while dealing with external perturbations as effectively as visual information.

In the baseline condition with vision obstructed (*BL_NV*), some muscle activities were observed in the APA phase. We speculate that it was due to the awareness of the upcoming perturbation impact, even though participants did not know the exact timing of the impact. Importantly, participants demonstrated the same level of muscle responses in the APA phase in conditions with auditory cue either with (*Training* condition) or without (*Catch* condition) the physical perturbation impact. This outcome indicates that participants were able to generate APAs relying on the auditory cue only.

4.2 Learning effects of using auditory information for postural control

It was reported that not only the availability of the visual information affects the generation of APAs, but also the quality of the visual information is important in generating effective APAs. For example, the visual information was manipulated in the previous studies by partially blocking the trajectory of the dropping load into the extended arms (Aruin et al. 2001), by using positive and negative glasses creating a misperception of the position of the pendulum during front perturbations (Mohapatra et al. 2012), or by using low-frequency light making the visual information about the forthcoming pendulum inaccurate (Mohapatra and Aruin 2013). All these studies reported delayed and/or diminished APA because participants were not able to accurately predict the timing of the external perturbations.

In the current study, we observed that participants displayed an earlier and stronger muscle response in the APA phase and a reduced muscle response in the CPA phase relying only on the auditory cue after repetitive exposures. The use of a combination of auditory cues and visual obstruction to examine the anticipatory muscle activities prior to the task of catching the ball while seated was described in the literature (Lacquaniti and Maioli 1987), and the authors reported inconsistent anticipatory activities. However, in that study, the perturbation was not fully predictable because the auditory cue did not provide sufficient information about the timing of the perturbation (dropped ball) (Lacquaniti and Maioli 1987). Our study presented a constant timing between the auditory cue and the physical impact of the perturbation, allowing the participants to build a connection between the auditory cue and the postural perturbation so that they were able of generating proper APAs using the auditory cue only after a short period of training. Our results also agree with the previous studies showing that people were able to optimize the APAs of the postural forearm during a seated unloading perturbation after 40-60 trials of training. In the previous studies, the timing of the unloading was triggered by the voluntary movement of the other forearm and, similarly to our study, it was learned through repetition training (Paulignan et al. 1989; Massion et al. 1999).

In the current study, we also observed a less effective APA during the early training trials (most prominently during the *Tr_1* block), exemplified by delayed latencies and smaller APA integrals of muscle activity. Some variables displayed a quick and large adjustment even after one block of training (i.e. APA and CPA integrals for ES and GM), while other variables demonstrated a gradual change during the first 4-5 blocks of training trials and then reached a plateau afterwards (i.e. APA and CPA integrals for RF and TA) (Fig.2 & Fig.3). We speculate that at the beginning of the training, the participants were not capable of using this relative novel auditory cue efficiently and the CNS was in an unstable state for generating appropriate APAs. However, after the participants were repetitively exposed to the auditory cue indicating the exact time of the perturbation, they gradually enhanced muscle responses and increased the COP posterior displacement in the APA phase. Consequently, smaller muscle responses were needed in the CPA phase. This observation indicates that overall young adults might need 20 to 25 repetitions to learn how to use a new auditory cue effectively to optimize the whole body response for the upcoming perturbation. It is important to note that we included an *Acclimation* condition (10 trials) when both the visual and auditory information was available before the *Training* condition in this study. These acclimation trials facilitated the abilities of participants to build the connection between the timing of the relative novel auditory cue and pendulum perturbation. Without such connections, they might need to perform more repetitive perturbations before they were able to generate proper APAs relying solely on auditory cue.

4.3 Patterns of muscle activity

Our results revealed that the study participants used reciprocal activation rather than muscle co-contraction during the APA phase (indicated by a larger R index than C index) in all the conditions when the moment of the pendulum release could be predicted (*BL_V* and *Training* conditions). Moreover, the calculated R and C indices showed that prior to the perturbation the ventral muscles were activated while the dorsal muscles were inhibited, which is in accord with the outcomes of the previous studies (Santos et al. 2010a; Chen et al. 2017). Specifically, in agreement with the previous literature, this reciprocal pattern was most prominent in the TA-MG pair with MG demonstrated large negative integrals representing muscle inhibition (Lee et al. 2015;

Chen et al. 2017). The use of reciprocal activation of muscles suggests that CNS was able to use an efficient strategy for postural control when the perturbation was predictable with either visual or auditory information available.

Similar to the findings of the previous study (Chen et al. 2017), our results showed a larger C index than R index during the CPAs phase, suggesting that the CNS increased the stiffness of the joints to enhance posture stability after the perturbation impact (Lee et al. 2015). However, it is interesting to note that with repetitive training, there was a decrease of the C-CPA index even though the R-CPA index remained the same. It seems that while the CNS mainly adopted the same co-contraction pattern in the CPA phase, it managed to regulate the level of muscle activities and maintain the posture stability in a more efficient manner.

This study included only young adults and all the pendulum perturbation training was performed in one session. Therefore, the results cannot be generalized to other populations and it is unknown whether the ability of using auditory cue effectively could last for a longer time. Older adults and other clinical populations showed delayed and ineffective APAs for postural perturbation (Kanekar and Aruin 2014; Aruin et al. 2015a). Future researches could examine whether these populations are capable of using the auditory cue by itself or combined with visual information to assist them in generation proper APAs for postural control, and also investigate the retention for this training effect.

5. Conclusions

The outcome of the study demonstrated that it is feasible to use an auditory cue to elicit APAs for an otherwise unpredictable postural perturbation. After an acclimation training of 10 trials with combined auditory and vision cues, and a short training of 20-25 trials with the auditory cue only, young adults were able to rely only on the auditory cue to generate APA comparable to that with visual information available. Additionally, the generation of APA in conditions with auditory cues resulted in the reduction of muscle responses during the balance restoration phase of postural control after the perturbation impact.

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Figure legends

Fig.1 A schematic representation of the experimental setup. The pendulum impact is applied to both the shoulders. m is an additional mass (5% of participant's body mass). BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked

Fig.2 EMG traces of the tibialis anterior (TA) and medial gastrocnemius (MG) of a representative participant during different conditions. The vertical dotted line shows the moment of perturbation impact (T0). Time scales are in seconds and EMG scales are in arbitrary units. BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked; Tr: training conditions. Tr_1 represents the beginning of the training, Tr_6 represents the middle of the training, and Tr_10 represents the end of the training. Note that the scales for both muscles during the *BL_NV* condition are bigger than the others, signifying the larger magnitude of muscle responses during the CPA phase.

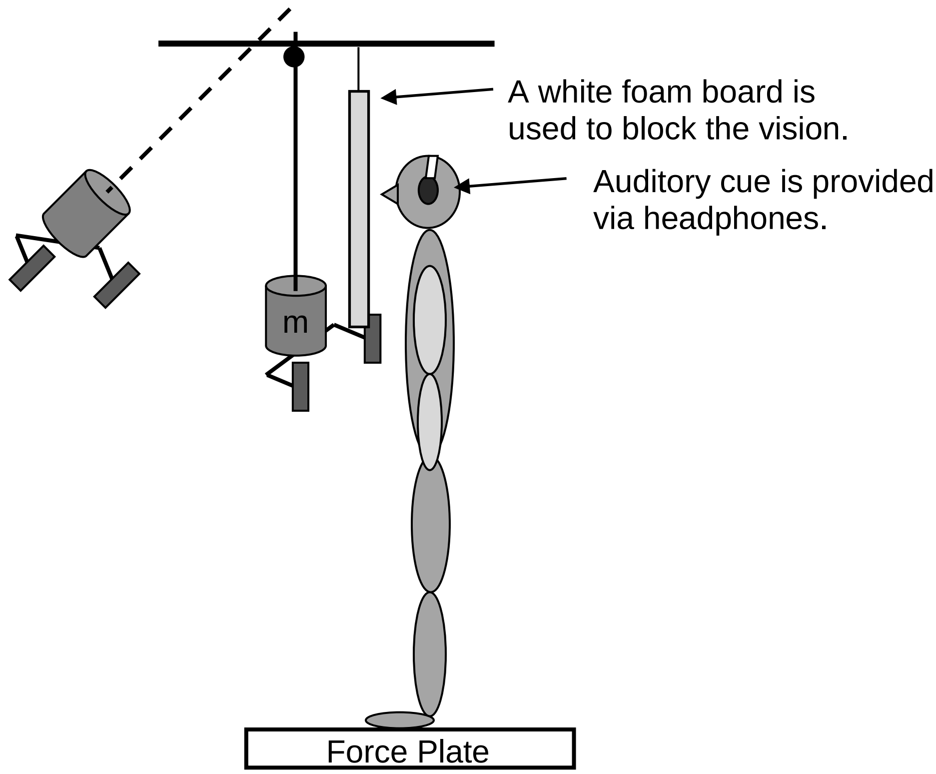
Fig.3 Mean (SE) of normalized EMG integrals of postural muscles during the anticipatory (APA) and compensatory (CPA) phases of postural control. Muscles included rectus abdominus (RA), erector spinae (ES), gluteus medius (GM), external obliques (EO), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and medial gastrocnemius (MG). BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked; Tr: training conditions

Note that positive values indicate muscle activation and negative values indicate muscle inhibition relative to background activities. Also note that the scale for MG is different than the other muscles. Tr_7 to Tr_9 conditions are not included in the figure.

Fig.4 Mean (SE) of C and R indices calculated for the whole-body model during the anticipatory (APA) and compensatory (CPA) phases of postural adjustments. BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked; Tr: training conditions

Fig.5 A) Mean (SE) of center-of-pressure (COP) displacements at T0. B) Mean (SE) of COP peak displacements after T0. Values are presented in meters, and positive values represent posterior displacements. BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked; Tr: training conditions. Note that Tr_7 to Tr_9 conditions are not included in the figure.

Fig.1



Condition	BL_V	BL_NV	Acclimation	Training	Catch
Number of trials	5	5	10	50	1
Visual information	☑	☒	☑	☒	☒
Auditory cue	☒	☒	☑	☑	☑

Fig.2

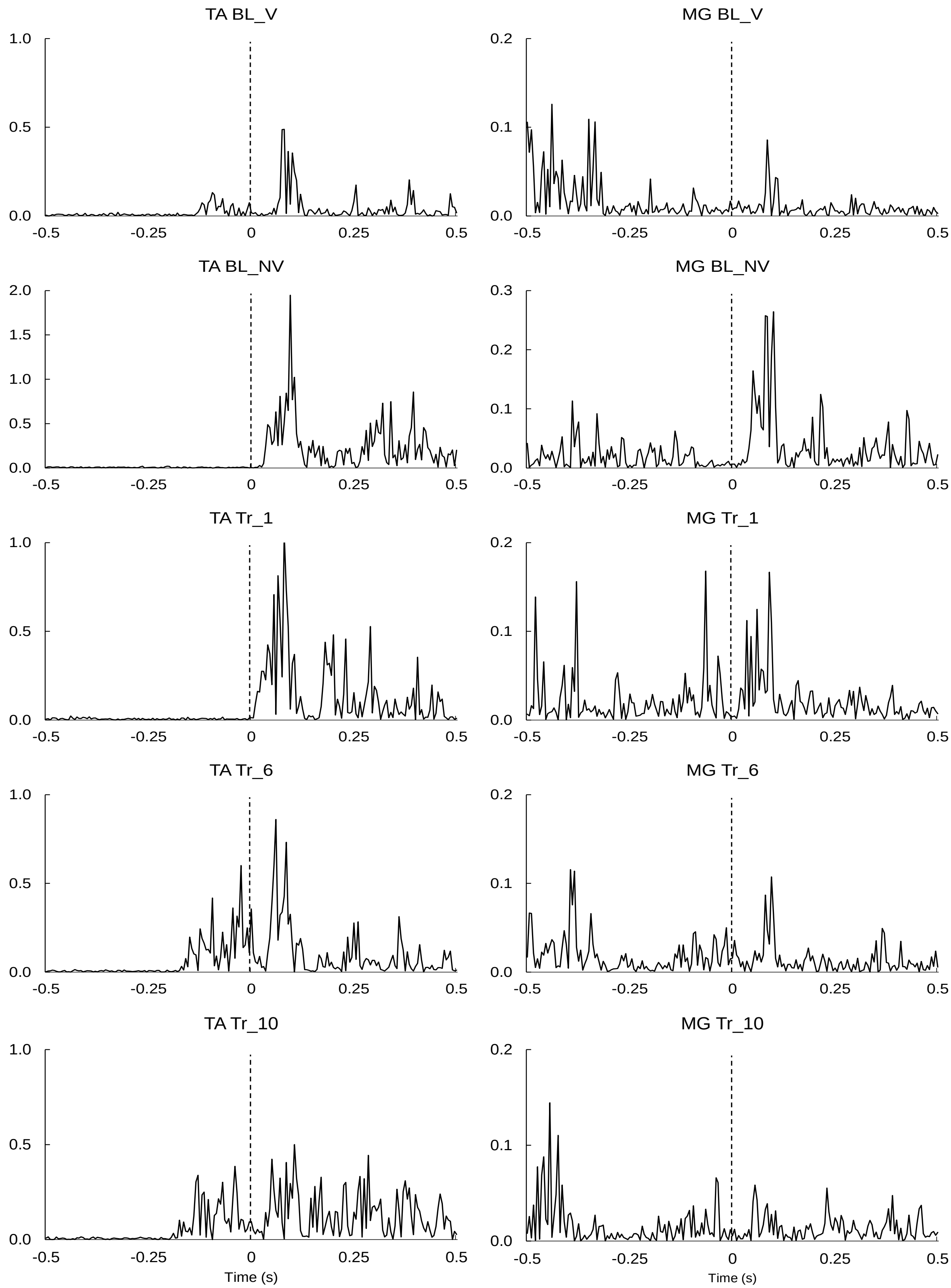
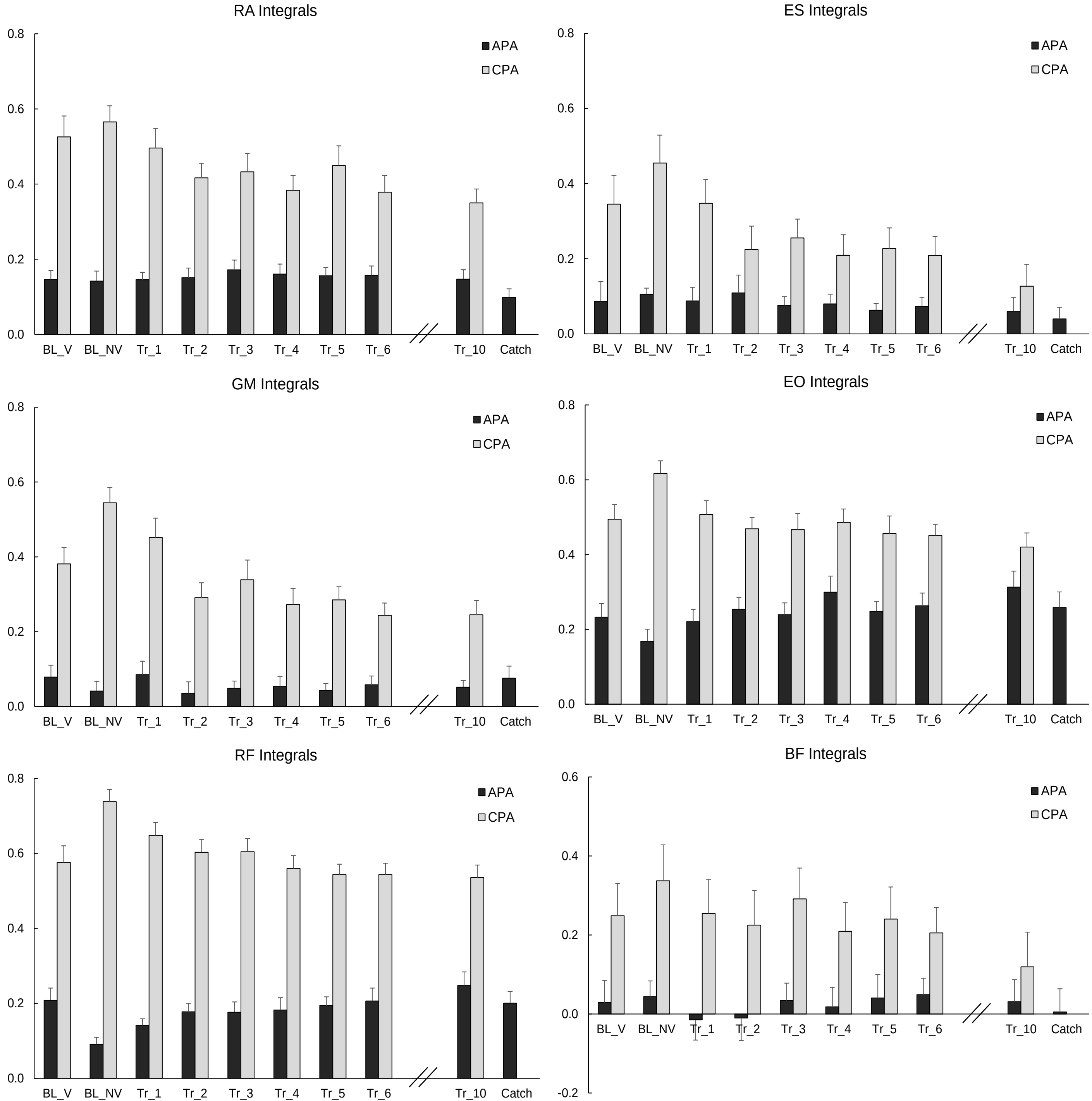

TA BL_V
MG BL_V
TA BL_NV
MG BL_NV
TA Tr_1
MG Tr_1
TA Tr_6
MG Tr_6
TA Tr_10
MG Tr_10
Time (s)
Time (s)

Fig.3



RA Integrals
ES Integrals
GM Integrals
EO Integrals
RF Integrals
BF Integrals
APA
CPA
BL_V
BL_NV
Tr_1
Tr_2
Tr_3
Tr_4
Tr_5
Tr_6
Tr_10
Catch
0.0
0.2
0.4
0.6
0.8
-0.2

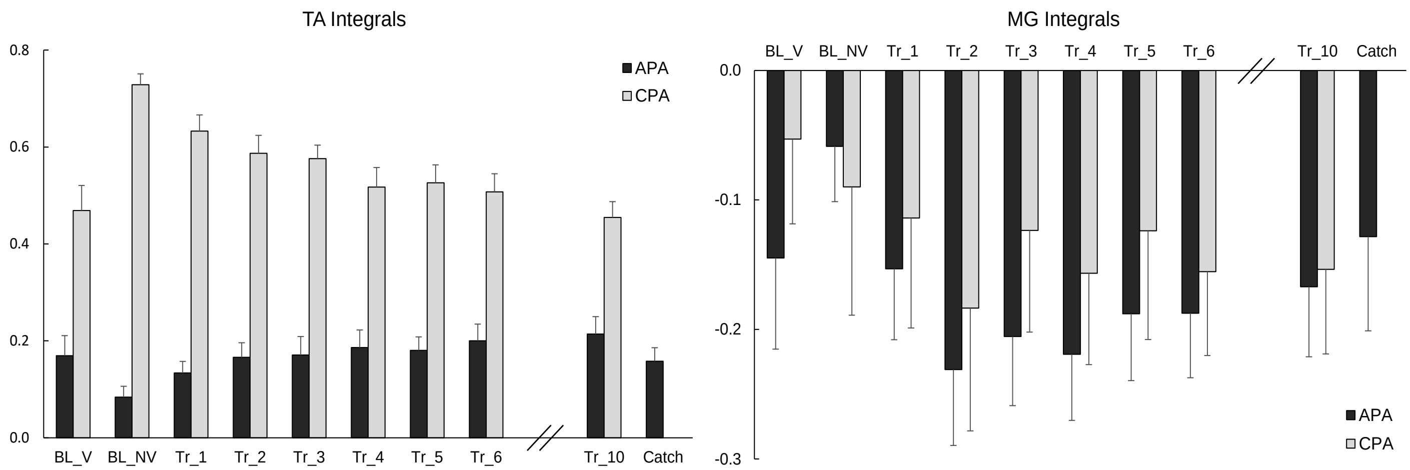

TA Integrals
0.8
0.6
0.4
0.2
0.0
APA
CPA
BL_V
BL_NV
Tr_1
Tr_2
Tr_3
Tr_4
Tr_5
Tr_6
Tr_10
Catch
MG Integrals
0.0
-0.1
-0.2
-0.3
APA
CPA

Fig.4

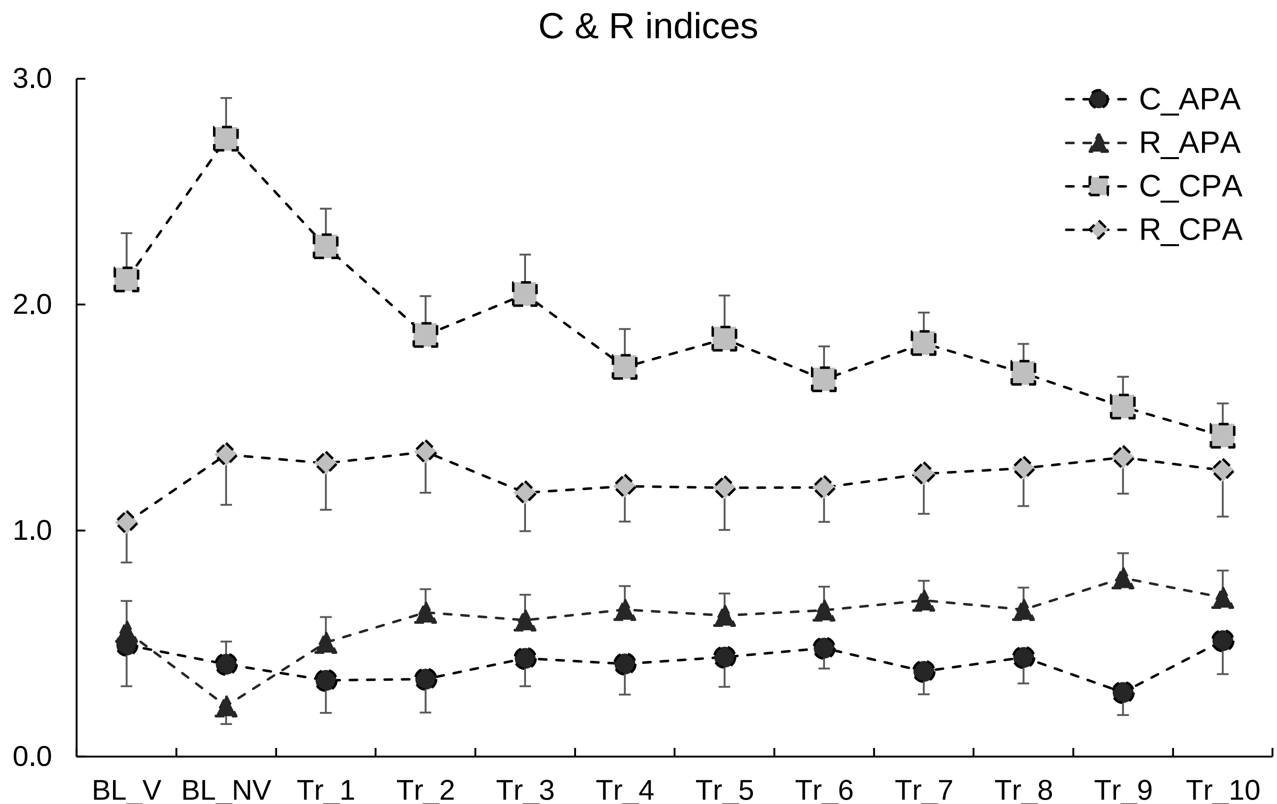

C & R indices
3.0
2.0
1.0
0.0
C_APA
R_APA
C_CPA
R_CPA
BL_V
BL_NV
Tr_1
Tr_2
Tr_3
Tr_4
Tr_5
Tr_6
Tr_7
Tr_8
Tr_9
Tr_10

Fig.5

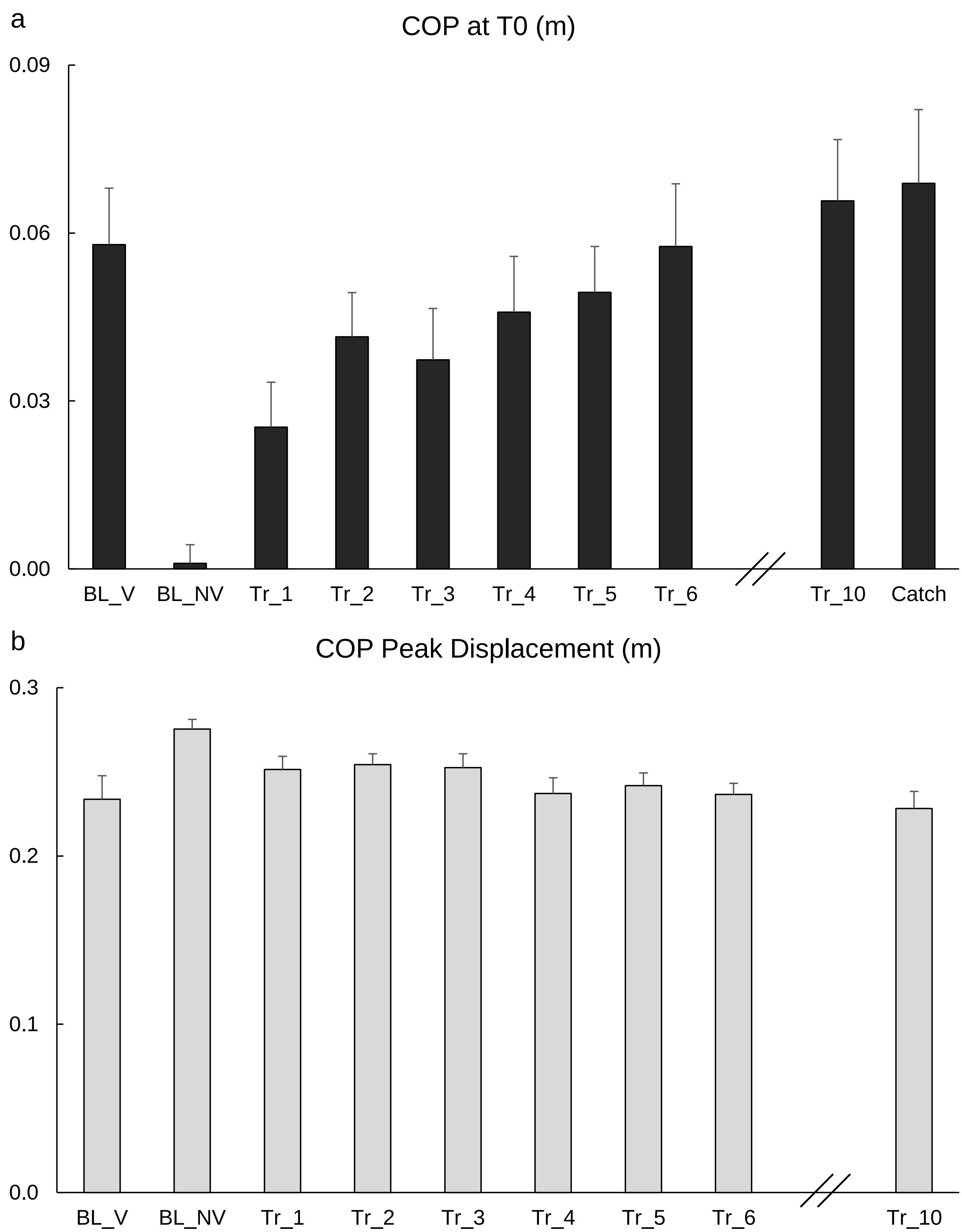

a
COP at T0 (m)
0.09
0.06
0.03
0.00
BL_V
BL_NV
Tr_1
Tr_2
Tr_3
Tr_4
Tr_5
Tr_6
Tr_10
Catch
b
COP Peak Displacement (m)
0.3
0.2
0.1
0.0
BL_V
BL_NV
Tr_1
Tr_2
Tr_3
Tr_4
Tr_5
Tr_6
Tr_10

Table 1. Mean ± SE of EMG latencies (in ms) of the postural muscles in each condition.

Muscle	BL_V	BL_NV	Tr_1	Tr_2	Tr_3	Tr_4	Tr_5	Tr_6	Tr_10	Catch
RA	-36 ±13	-3 ±10	-26 ±11	-44 ±14	-55 ±12	-34 ±12	-37 ±14	-62 ±15	-55 ±16	-123 ±11
ES	-158 ±26	-22 ±2	-140 ±0	-149 ±22	-170 ±29	-121 ±12	-132 ±10	-140 ±15	-61 ±45	-120 ±14
GM	-9 ±17	29 ±13	-5 ±17	-8 ±17	7 ±19	-7 ±22	1 ±18	-18 ±17	-4 ±17	-51 ±14
EO	-122 ±16	-24 ±13	-87 ±12	-88 ±13	-94 ±14	-116 ±15	-99 ±15	-113 ±15	-126 ±15	-156 ±18
RF	-161 ±18	-33 ±13	-89 ±11	-108 ±14	-104 ±14	-100 ±16	-120 ±14	-122 ±16	-142 ±12	-143 ±17
BF	-242 ±21	-2 ±26	-200 ±20	-181 ±19	-181 ±8	-215 ±19	-206 ±13	-197 ±23	-211 ±15	-173 ±26
TA	-122 ±22	-16 ±12	-65 ±15	-75 ±17	-75 ±17	-82 ±20	-92 ±15	-95 ±19	-112 ±18	-112 ±11
MG	-223 ±19	3 ±29	-121 ±44	-168 ±28	-159 ±29	-160 ±27	-149 ±30	-206 ±15	-182 ±19	-218 ±20

BL_V: baseline with visual information available; BL_NV: baseline with visual information blocked; Tr: training conditions.

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