Response inhibition and avoidance of virtual obstacles during gait in healthy young and older adults

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Short title: Response inhibition and obstacle avoidance

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Abstract

Adjustments of preplanned steps are essential for fall avoidance and require response inhibition. Still, inhibition is rarely tested under conditions resembling daily living. We evaluated the ability of young and older adults to modify ongoing walking movements using a novel precision step inhibition (PSI) task combined with an auditory Stroop task.

Healthy young (YA, n=12) and older (OA, n=12) adults performed the PSI task at 4 individualized difficulty levels, as a single and dual task (DT). Subjects walked on a treadmill by stepping on virtual stepping stones, unless these changed color during approach, forcing the subjects to avoid them.

OA made more failures (40%) on the PSI task than YA (16%), but DT did not affect their performance. In combination with increased rates of omitted Stroop task responses, this indicates a “posture first” strategy. Yet, adding obstacles to the PSI task significantly deteriorated Stroop performance in both groups (the average Stroop composite score decreased by 13% in YA and 27% in OA). Largest deficit of OA was observed in rates of incorrect responses to incongruent Stroop stimuli (OA 35% and YA 12%), which require response inhibition. We concluded that the performance of OA suffered specifically when response inhibition was required.

Keywords

Obstacle avoidance; older adults; dual task; response inhibition; Stroop task; accidental falls

1. Introduction

During gait, we plan swing limb trajectories for steps ahead using visual information about the environment in a feed forward manner (Patla & Vickers, 1997). If perturbed, one needs to adjust a planned step using feedback information both on whole body and limb motion (Patla & Vickers, 1997) and on the surrounding environment (Maki & McIlroy, 2007; Patla & Vickers, 1997). This requires inhibition, because the preplanned step needs to be stopped before finding an alternative foot landing position. Therefore, inhibition is an important skill, lack of which might lead to increased instability and risk of falling, especially given the age related deterioration of inhibitory abilities (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Verbruggen & Logan, 2008).

In the past, response inhibition ability was typically tested in the arms (Coxon, Stinear, & Byblow, 2007; Coxon, Van Impe, Wenderoth, & Swinnen, 2012). More recently however, several groups have attempted to assess response inhibition in the lower limbs in healthy older adults (OA), thereby attempting to bridge the gap with the field of arm motor control (Redfern, Jennings, Mendelson, & Nebes, 2009; Sparto et al., 2013; Tseng, Stanhope, & Morton, 2009; Uemura, Oya, & Uchiyama, 2013). These experiments have confirmed a link between inhibition and motor reactions, more specifically postural sway and step initiation.

With respect to gait it is interesting to relate these findings on response inhibition to falls. It is known that falls are associated with an impaired ability to execute a fast voluntary step (Lord & Fitzpatrick, 2001). This impairment might be due to inhibitory deficits as it has been shown that inhibition of inappropriate postural adjustments is required for a timely onset of a voluntary stepping reaction (Sparto et al., 2013; Uemura et al., 2013). Furthermore, the ability to modify an initiated step in response to desired foot landing position shifts declines with aging (Tseng et al., 2009). However, these experiments remain somewhat remote to circumstances of falling. They focused mainly on movement preparation (Lord & Fitzpatrick, 2001; Sparto et al., 2013; Uemura et al., 2013) and were limited to step initiation, while most falls occur during walking (Robinovitch et al., 2013; van Dieën & Pijnappels, 2008). Therefore, we aimed to measure the ability of OA to modify ongoing movements during walking. To this aim, we used an obstacle avoidance task (Moraes & Patla, 2006; Weerdesteyn, Nienhuis, & Duysens, 2005), as a common fall related situation, and included an element of inhibition in order to work in parallel with the arm movement experiments on response inhibition. Our specific walking task required stepping towards a precise target and then inhibiting that step following a sudden “stop” signal (Potocanac et al., 2014). This is a form of obstacle avoidance that stresses the need for inhibition and adjustment of preplanned steps as the obstacles initially represent targets for subjects to step on. Hence, this walking task requires inhibition of ongoing precise steps and we refer to it as precision step inhibition (PSI) task throughout this paper. Our previous work established a protocol that proved to be feasible, although demanding, in young adults (YA) (Potocanac et al., 2014). However, it remains to be seen whether this task is appropriate for use in OA, the population of interest with respect to falls.

To further test for response inhibition we added a cognitive dual task (DT) that also requires inhibition. Including a DT in our experiment is not only interesting from the inhibition point of view, but also adds ecological validity with respect to falls. During daily living one almost always performs multiple tasks while walking, and with advancing age even simple cognitive tasks can have a detrimental effect on postural stability and obstacle avoidance (Boisgontier et al., 2013; Shumway-

Cook, Woollacott, Kerns, & Baldwin, 1997; Weerdesteyn, Schillings, van Galen, & Duysens, 2003; Woollacott & Shumway-Cook, 2002). Indeed, cognitive decline has been associated with an increased risk of falls (Deandrea et al., 2010; Mirelman et al., 2012) and some studies suggested that changes in DT performance are significantly associated with an increased risk for falling amongst OA (Beauchet et al., 2008, 2009; Faulkner et al., 2007). The auditory Stroop task (Hegeman et al., 2012; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008; Weerdesteyn et al., 2003) is especially suited in this context, since subjects respond to congruent and incongruent stimuli, but only incongruent stimuli require inhibition. Therefore, evaluating the performance in response to the two types of stimuli separately provides insight into inhibitory demands and capacities, while at the same time controlling for dual tasking per se, similar to the methods used by others (Redfern et al., 2009). Finally, a DT experiment allows for inferences about task prioritization. If response inhibition is “global” (Aron & Verbruggen, 2008; Coxon et al., 2007), i.e. inhibitory resources are shared for the two tasks, we should be able to see task interference. Furthermore, if the PSI task is prioritized over the Stroop task, the subjects’ performance on the Stroop task would deteriorate, while the PSI task performance would remain stable. On the other hand, if there is no clear prioritization, the performance on both tasks would suffer under DT conditions. It has been suggested that OA use a “posture-first strategy”, prioritizing stability in demanding conditions (Brauer, Woollacott, & Shumway-Cook, 2002; Schrodtt, Mercer, Giuliani, & Hartman, 2004; Siu & Woollacott, 2007). A similar strategy was observed in stroke patients under conditions of obstacle avoidance (Smulders, van Swigchem, de Swart, Geurts, & Weerdesteyn, 2012). However, for obstacle avoidance in healthy OA, some previous experiments reported that adding a DT affected the success of obstacle avoidance (Chen et al., 1996; Hegeman et al., 2012; Weerdesteyn et al., 2003), whereas others observed no DT effect, although they reported subtle changes in gait speed and stride length, probably due to ample time available for preparation for obstacle avoidance (Siu et al., 2008). The question remains whether healthy OA would prioritize posture more when the obstacle avoidance task is made more difficult, for example by adding an aspect of response inhibition. This would go in line with the suggestion that prioritization is a dynamic process, dependent on the difficulty of the tasks involved (Boisgontier et al., 2013; Shumway-Cook et al., 1997). Hence it is important to use demanding motor and cognitive tasks if one wants to gain insight into task prioritization.

To summarize, the aim of this study was threefold. Firstly, to assess the feasibility of using the newly developed PSI task in OA and to compare their performance to the previously reported performance of YA (Potocanac et al., 2014). We expect OA to have more difficulty performing the PSI task, which should be reflected in higher failure rates and more time needed for successful obstacle avoidance. Secondly, to evaluate the inhibitory requirements of the Stroop tasks by evaluating the performance in response to congruent and incongruent Stroop stimuli while performing either cued walking or the PSI task simultaneously. We expect both the PSI and Stroop tasks to pose inhibitory requirements, which would be manifested by deteriorated performance in response to incongruent stimuli compared to congruent, as only incongruent stimuli required inhibition. Furthermore, we expect the two tasks to use shared resources, which should result in task interference, and we expect OA to show deteriorated performance when inhibition is required. Finally, if task interference is present, we hypothesize that OA would prioritize the PSI task, lending support to the “posture-first strategy”.

2. Methods

2.1. Subjects

Twelve healthy YA (mean age 23 ± 2.4 years, range 21-30 years, 5 women) and twelve healthy OA (mean age 72 ± 3.8 years, range 66-78 years, 5 women) participated in this study. The healthy elderly were recruited locally. Subjects had no problems with their musculoskeletal system, had good eye vision and were not color blind. Older subjects had no cognitive impairments (MMSE score > 27). The experiment was approved by the local ethical committee and performed according to the declaration of Helsinki. All subjects gave their informed consent prior to participating in the study.

2.2. Precision step inhibition task

The experimental setup is illustrated in figure 1 and previously described in detail (Potocanac et al., 2014).

Subjects walked on the C-Mill (ForceLink, Culemburg, the Netherlands) at a constant speed of 0.83 m/s. This system, comprising a software package and an instrumented treadmill, is able to project patches of light onto the treadmill relative to the subjects' foot placement, based on center of pressure patterns. These patches of light served as stepping stones and subjects were instructed to walk by stepping on the stones, unless a stone suddenly changed color during approach. In this case it was to be considered an obstacle and to be avoided by either shortening or lengthening the step. To do so, subjects needed to inhibit their ongoing step aimed at the stepping stone and find an alternative foot landing position. Stepping on or to the side of the obstacle was considered a failure. Distance between the stepping stones (i.e. step length) was individually adjusted to be comfortable and was held constant during the experiment.

The occurrence of color changing stones was random and their position was defined by the available response distance (ARD), the distance between subject's center of pressure and a virtual threshold in front of the subject (figure 1c). The first stepping stone ahead of this threshold changed color, i.e. the stepping stone that was about to change color could be situated just behind this virtual threshold or at an additional distance, corresponding to the distance between the virtual threshold and the position of the next stepping stone. Therefore, the minimal distance to the stepping stone that was about to change color was ARD, while the maximal possible distance could be "ARD + step length". ARD was used to manipulate task difficulty. As ARD decreased, the task became more difficult because less time was available to inhibit a previously initiated step aimed at the target, and to find an alternative. However, depending on individual step length, for any given ARD the phase of the step cycle at which the stepping stone changed color could differ. The largest between-subject difference in average step length was 10 cm in OA and 8 cm in YA, meaning that, given the speed of 0.83 m/s and a step cycle of 1 s, there could be a change of about 12% and 10% of the step cycle for any given ARD condition in OA and YA, respectively. Table 1 shows data on step lengths. Given that our subjects walked at a constant speed of 0.83 m/s it is possible to calculate the time equivalent corresponding to each ARD by dividing ARD by the treadmill speed as $ART (ms) = ARD (mm) / 0.83$. ART values corresponding to ARD values used in our experiment are shown in table 2. However, one should keep in mind that this ART definition differs from other obstacle avoidance experiments (Chen et al., 1996; Chen, Ashton-Miller, Alexander, & Schultz, 1994; Hegeman et al., 2012; Weerdesteyn, Nienhuis, & Duysens, 2005; Weerdesteyn, Nienhuis, Mulder, & Duysens, 2005), who used kinematic data of the foot as a reference point, and was not manipulated directly, but rather the distance from the subject's center of pressure to the obstacle (i.e. ARD).

2.3. Experimental protocol

We followed the experimental protocol described in Potocanac et al. (2014) and determined ARDs considered “easiest” individually after gradual introduction and practice of the task. Once familiar with the task the “easiest” level of difficulty was determined by performing short versions of the task starting from a difficulty level at which all subjects were expected to be able to perform the PSI task (as based on a pilot study; OA ARD = 700 mm, YA ARD = 600 mm). Three obstacles were presented at this task difficulty and, if avoided successfully, task difficulty was increased (by decreasing the ARD by 50 mm) until the subject's first failure. This procedure was performed twice and the mean value of ARDs at which the failures occurred was used as “easiest” level for the main experiment.

The protocol consisted of a baseline walking task condition (cued walking without obstacles) followed by 4 conditions with increasing difficulty. The individually determined “easiest” level was used for the starting condition and for the subsequent conditions the ARD was decreased each time by 50 mm. Each condition consisted of 20 obstacles that could appear at either foot, at a frequency of 7 per minute. After a break, subjects repeated the same PSI task conditions with an auditory DT. Cued walking without any obstacles was used as a baseline for Stroop task performance. Participants were instructed to perform both the PSI and the Stroop tasks to the best of their abilities.

2.4. Auditory dual (Stroop) task

The auditory DT stimuli consisted of words “high” and “low”, spoken in a high or low pitched voice. The stimuli were either congruent (spoken word matched the pitch used) or incongruent (the word did not match the pitch) and subjects had to respond as fast as possible by verbalizing the pitch. The stimuli were presented continuously, randomized, with the interstimulus interval set to approximately 1.2 s. Subjects’ responses were recorded wirelessly.

2.5. Data analysis

We verified failures on the PSI task by video recordings of the experiment. Failure rates were calculated by dividing the number of failures by the total number of obstacles presented. Performance of OA on the PSI task was compared to previously reported performance of YA (Potocanac et al., 2014).

The Stroop task resulted in several hundred responses per condition. Therefore, a computerized analysis program was devised that extracted and recognized the spoken words, based on the Mel-frequency cepstrum coefficients matched to previously created Gaussian mixture models of words “high” and “low”. The accuracy of the word recognition, as evaluated by 10-fold cross validation of the learning set consisting of 703 sounds, was 93.5%. The pitch analysis based on Subharmonic-to-Harmonic Ratio (Sun, 2002) resulted in 100% accuracy. Responses could be either correct, incorrect (i.e., wrong reply given) or omitted (i.e., no reply given). Response latency was defined as time between the stimulus offset and the response onset. Latencies of correct responses and rates of correct, incorrect and omitted responses were analyzed for congruent and incongruent stimuli separately. This allowed for a detailed evaluation of performance: as performance deteriorates one first takes longer to respond correctly, makes more incorrect responses, and eventually might stop responding altogether. Furthermore, since good performance on the Stroop task means both accurate and fast responses, a composite score combining speed and accuracy was calculated as a ratio of the rate of correct responses (%) and average latency of correct responses (s) (Hegeman et al., 2012). This composite score enables easy assessment of the overall Stroop performance and was

calculated for incongruent and congruent stimuli in each PSI task condition. Analyses were performed using VOICEBOX toolbox (Brookes, 1997) and MATLAB 2011b (Mathworks, Natick, MA, USA).

Due to technical problems, two YA did not perform the DT and the Stroop task data of one YA and PSI task data of one OA were unavailable.

2.6. Statistical analysis

PSI task failures were analyzed using a 2 (age) x 4 (difficulty conditions) x 2 (single task (ST) vs. DT) repeated measures ANOVA procedure, followed by a Tukey HSD post-hoc test. Additionally, individually determined “easiest” level ARDs and failure rates were compared between the groups using a Mann-Whitney U test. Stroop task performance (composite score, latencies of correct responses and rates of correct, incorrect and omitted responses) was analyzed using a 2 (age) x 5 (baseline and 4 difficulty conditions) x 2 (congruence) repeated measures ANOVA procedure, followed by a Tukey HSD post-hoc test. Analyses were performed using Statistica 10 (StatSoft, Tulsa, OK, USA) with level of statistical significance set at $\alpha = 0.05$.

3. Results

3.1. Precision step inhibition task performance

On average, the “easiest” level ARD was 655 ± 15 mm (range 650 – 700 mm) in OA, while in the YA this was 521 ± 54 mm (range 450 – 600 mm). These ARD values correspond to average ARTs of 786 ± 18 ms (range 780 – 840 ms) in OA and 625 ± 65 ms (range 540 – 720 ms) in YA. Mann-Whitney U test showed a statistically significant difference in “easiest” level ARD between age groups ($p < 0.001$). Figure 2 clearly shows that the range over which the two groups could be tested differed, although there was some overlap. This difference in range was due to the older subjects starting to fail sooner than the YA during the process of determining individual “easiest” ARD level. Poor performance of OA was also reflected in higher failure rates of OA compared to YA in the “easiest” condition, for both ST ($p = 0.005$) and DT ($p = 0.006$). In OA these rates were on average $40 \pm 22\%$ (range 15% – 80%) for the ST and $45 \pm 12\%$ (range 30% – 60%) for the DT, while in YA these were $16 \pm 11\%$ (range 5% – 35%) for the ST and $27 \pm 11\%$ (range 15% – 45%) for the DT. Finally, for the range of overlapping ARDs, OA had higher failure rates than YA. Adding a DT increased failure rates in all conditions for both age groups.

Although most subjects had an increase in failure rates with increasing PSI task difficulty there were some subjects in the OA group that showed improvement in task performance over time, resulting in no significant main effect of age for the repeated measures ANOVA. We did find significant main effects of task ($p = 0.002$) and difficulty ($p < 0.001$) and an interaction of age and difficulty ($p < 0.001$). Failure rates were higher when the PSI task was performed under DT conditions and as ARD decreased. However, the difficulty effects were driven by YA and not significant in the group of OA alone.

3.2. Stroop task performance

3.2.1. Composite scores

Composite score data are shown in figure 3. Repeated measures ANOVA showed significant main effects of age ($p = 0.03$), indicating deteriorated performance of OA, and PSI task difficulty ($p < 0.001$), indicating worse performance during PSI compared to baseline cued walking ($p < 0.004$ for each of the difficulty conditions). A significant main effect of congruence ($p < 0.001$) indicated performance was generally lower for incongruent stimuli, but a significant interaction of age and congruence ($p = 0.02$) indicated that only OA performed significantly worse in response to incongruent stimuli compared to congruent ($p < 0.001$). Additionally, age resulted in deteriorated performance only in response to incongruent stimuli, when OA performed significantly worse than YA ($p \leq 0.01$). Combining these two results shows that OA and YA performed equally well in response to the congruent stimuli and only the performance of OA deteriorated when stimuli became incongruent.

3.2.2. Rates of correct responses

Average rates of correct responses during baseline walking were $83.2 \pm 16.4\%$ and $81.6 \pm 16.2\%$ in YA and $78.1 \pm 18.1\%$ and $52.4 \pm 32.8\%$ in OA, for congruent and incongruent stimuli respectively (Figure 4a). Repeated measures ANOVA showed significant main effects of age (OA performed worse than YA, $p = 0.003$), PSI task difficulty (performance on the PSI task deteriorated compared to baseline cued walking, $p = 0.004$), congruence (performance deteriorated in response to incongruent stimuli, $p = 0.001$) and interaction of age and congruence ($p = 0.01$). OA performed worse than YA in response to incongruent stimuli ($p < 0.001$), but equally well when stimuli were congruent.

3.2.3. Rates of incorrect responses

In line with correct responses, OA showed, on average, higher rates of incorrect responses than YA (Figure 4b), both in response to congruent and incongruent stimuli (congruent YA = $5.4 \pm 8.4\%$, OA = $8.6 \pm 6.4\%$; incongruent YA = $5.3 \pm 5.7\%$, OA = $31.3 \pm 25.2\%$). Repeated measures ANOVA showed significant main effects of age ($p = 0.01$), congruence ($p = 0.004$) and significant interaction effects of age and congruence ($p = 0.01$), PSI task difficulty and congruence ($p < 0.001$), and PSI task difficulty, age and congruence ($p < 0.001$). Rates of incorrect responses were higher in OA and for responses to incongruent stimuli. OA performed worse than YA in response to incongruent stimuli ($p = 0.004$), but equally well when stimuli were congruent. The congruence effect was only significant in OA, who performed worse in response to incongruent stimuli as compared to congruent ($p = 0.002$). PSI task difficulty x congruence interaction was such that the congruence effects were significant when obstacles were included in the PSI task (all difficulty levels, $p \leq 0.008$), but not during baseline walking. Finally, significant results for the three way interaction showed that only the performance of OA in response to congruent and incongruent stimuli differed already during baseline cued walking ($p = 0.017$).

3.2.4. Rates of omitted responses

Rates of omitted responses during baseline walking were $11.5 \pm 15.3\%$ and $13.1 \pm 14.9\%$ in YA and $13.3 \pm 14.0\%$ and $16.3 \pm 17.1\%$ in OA for congruent and incongruent stimuli, respectively (Figure 4c). When obstacles were added to baseline cued walking these rates were $10.9 \pm 8.2\%$ and $8.5 \pm 6.2\%$ in YA and $25.2 \pm 18.0\%$ and $27.0 \pm 16.5\%$ in OA for congruent and incongruent stimuli, respectively. We found a significant interaction between age and PSI task difficulty ($p = 0.04$), indicating OA omitted

significantly more responses than YA for the two most difficult PSI task conditions, compared to baseline cued walking.

3.2.5. Latencies of correct responses

Finally, for the response latencies (Figure 4d), we found a significant main effect of congruence ($p < 0.001$) and interaction effects of age and congruence ($p = 0.001$) and of PSI task difficulty and congruence ($p = 0.04$). Both age groups showed longer latencies for correct responses in response to incongruent compared to congruent stimuli (both $p < 0.001$). On average, the YA showed shorter latencies than OA, both in response to congruent and incongruent stimuli (baseline walking: congruent YA = 0.43 ± 0.07 s, OA = 0.46 ± 0.13 s; incongruent YA = 0.50 ± 0.09 s, OA = 0.63 ± 0.17 s). OA's responses to incongruent stimuli took significantly longer than responses of YA to congruent stimuli ($p = 0.03$). PSI task difficulty did not affect responses to incongruent stimuli, but it did influence the latencies of correct responses to congruent stimuli, which were longer for the two easiest difficulty levels compared to baseline cued walking ($p < 0.025$).

4. Discussion

In the first part of the discussion we focus on PSI task performance of both groups, analyzing task difficulty and failure rates. The second part of the discussion focuses on performance under DT conditions. Performance of OA and YA on the Stroop task and the interference between the two tasks are discussed with respect to the inhibitory requirements of the two tasks, subjects' abilities, and task prioritization.

4.1. Performance on the precision step inhibition task

The main aim of this paper was to explore whether OA could be tested using our novel PSI task that evaluates response inhibition by requiring adjustments of ongoing, precisely aimed steps. OA successfully performed the PSI task at different, individually adjusted difficulty levels, however their performance was worse than previously reported performance of YA (Potocanac et al., 2014). This was evident by higher failure rates at both individually adjusted "easiest" ARD levels (which differed, but were performed after equal amounts of practice in both groups) and for overlapping ARD levels (which reflect absolute task difficulty).

In general, this increased failure rate is in line with age related decline in inhibitory abilities measured in a hand test of response inhibition (Coxon et al., 2012) and consistent with previous experiments showing deteriorated ability of older adults to initiate fast voluntary steps (Lord & Fitzpatrick, 2001) and modify desired foot landing positions (Tseng et al., 2009). Furthermore, our data are in line with previous obstacle avoidance experiments showing deteriorated ability of older adults to avoid physical (Hegeman et al., 2012; Weerdesteyn, Nienhuis, & Duysens, 2005) and virtual obstacles (Chen et al., 1996, 1994). However, some results from the present study differed from previous obstacle avoidance studies, probably because our PSI task stressed inhibition, as our subjects initially aimed to step onto stepping stones turning into virtual obstacles (while previous work did not require precision stepping). In particular, previous experiments on obstacle avoidance found that OA of comparable age had success rates over 90% with ARTs over 350 ms for avoidance of physical obstacles (Hegeman et al., 2012; Weerdesteyn, Nienhuis, & Duysens, 2005) and 450 ms for

avoidance of virtual obstacles (Chen et al., 1996, 1994). In contrast, in our setup, OA needed more time and had failure rates of 40.5% for ARDs of 654.5 mm (equivalent of 785.5 ms at a treadmill speed of 0.83 m/s). This finding was in line with our previously reported data of YA (Potocanac et al., 2014), and confirms that performing the PSI task requires more time. This could be related to increased task complexity, as obstacles are presented on both sides, consistent with previous data showing a significant delay in onset of reactions to suddenly appearing obstacles when switching from a one sided to a two sided paradigm (Marigold, Weerdesteyn, Patla, & Duysens, 2007). Additionally, it is possible that in previous experiments (Hegeman et al., 2012; Weerdesteyn, Nienhuis, & Duysens, 2005) subjects fixated their gaze on the obstacle prior to its release, while in our case they did not know where the stepping stone turning into an obstacle would be positioned. However, some of the differences in timing could also be caused by the differences in the technical setup. In our experiment the distance from the subjects' center of pressure to the stepping stone to change color was manipulated, and not ART directly. Furthermore, the differences in subjects' step lengths could cause variability in the phase of the gait cycle in which an obstacle was presented of about 10%-12% for any given ARD, which could account for about 100 ms of the additional time needed for successful obstacle avoidance.

4.2. Inhibitory requirements and abilities

The second aim of this paper was to assess inhibitory requirements of the two tasks, the potential use of shared inhibitory resources and a possible age related decline in inhibitory abilities. We hypothesized both tasks would require inhibition, thus causing interference effects and providing evidence that both tasks tapped into the same pool of global response inhibition. Furthermore, we expected deteriorated performance in the group of OA.

The Stroop task in itself requires motor inhibition with respect to the act of speaking. To give a correct response to incongruent stimuli, one needs to inhibit the processing of irrelevant information. Therefore, similar to work of Redfern et al. (Redfern et al., 2009), the difference in performance between congruent and incongruent Stroop stimuli can indicate inhibition abilities while controlling for the listening and speaking elements of the Stroop task. Although some studies reported no significant effect of congruence during obstacle avoidance (Siu et al., 2008; Siu & Lugade, 2008), we found the rates of correct responses to incongruent stimuli to be lower than when responding to congruent stimuli (on average about 4% in YA and 28% in OA). These findings are in line with previous reports of incongruent auditory Stroop stimuli during obstacle avoidance resulting in a decreased composite score consisting of accuracy and latency measures (Hegeman et al., 2012) and show that the performance deteriorates when inhibition is required, i.e., in response to incongruent Stroop stimuli. The importance of inhibition for successful execution of these tasks is further supported by the fact that congruence affected the rate of incorrect responses in YA only when obstacles were added to baseline cued walking, indicating that the additional inhibitory requirements are indeed related to obstacle avoidance and not just dual tasking (i.e., cued walking, listening and talking). In addition, interference between the two tasks requiring response inhibition, supports the notion of a "global" mechanism of response inhibition when speed is essential (Aron & Verbruggen, 2008; Coxon et al., 2007).

Finally, in line with previous findings indicating that inhibitory abilities deteriorate with increasing age (Kramer et al., 1994; Verbruggen & Logan, 2008), we found that OA performed worse than YA

only when the Stroop task required inhibition, i.e. when responding to incongruent Stroop stimuli. OA performed as well as YA in response to congruent Stroop stimuli, which required no inhibition.

4.3. Task prioritization

When combining PSI with the Stroop task, OA's performance on the PSI task did not deteriorate, but they did perform worse on the Stroop task, which indicates that older subjects prefer a "posture first" strategy under the present conditions. This is in line with previous studies reporting that OA prioritize stability when it is threatened (Brauer et al., 2002; Schrodtt et al., 2004). In contrast, Hegeman et al. (Hegeman et al., 2012) reported diminished obstacle avoidance performance in a group of OA when using an auditory Stroop task in combination with obstacle avoidance during treadmill walking. This apparent discrepancy might be due to several elements. Firstly, the PSI task was more difficult, thereby requiring potentially more cognitive resources in itself (Boisgontier et al., 2013). Secondly, there was an age difference between the experimental groups in these two studies. Average age of OA in our study was 72 years (range 66-78 years), while Hegeman's subjects were on average 60 years old. It has been previously suggested that the decline in performance during obstacle avoidance occurs at about 70 years of age (Weerdesteyn, Nienhuis, & Duysens, 2005). It is possible that the stability of our subjects was threatened more and therefore needed to be prioritized.

In contrast to OA, in YA the addition of the Stroop task significantly increased failure rates on the PSI task (on average by 14.6%). This is in line with a study by Weerdesteyn et al. (Weerdesteyn et al., 2003), who reported a failure rate increase of 11% during obstacle avoidance with a Stroop DT (Weerdesteyn et al., 2003). In contrast others (Brown, McKenzie, & Doan, 2005; Siu et al., 2008) did not see an effect of the DT on obstacle avoidance success rates in YA and attributed this to prioritization of the walking task. Apparently, in our case, the YA did not prioritize the PSI task, as indicated by the bidirectional interference between the two tasks. A possible explanation lies in the fact that both of our tasks were more demanding and therefore perhaps more prone to DT interference. We used a continuous Stroop task, with stimuli presented every 1.2 s on average, while Siu et al. (Siu et al., 2008) used a single Stroop stimulus per walking trial and Brown et al. (Brown et al., 2005) used a verbal reaction time task. Furthermore, we used precision stepping under time pressure on a treadmill, while others (Brown et al., 2005; Siu et al., 2008) used overground walking. All these differences help explain why the Stroop task performance was also affected by DT interference. More generally it is clear that the issue of prioritization depends heavily on task difficulty. This lends support to the proposals that prioritization is a dynamic process (Kelly, Eusterbrock, & Shumway-Cook, 2013) that "is likely to be ruled by a controlled/automatic ratio that is imposed by the difficulty of the tasks rather than a prioritization framework" (Boisgontier et al., 2013).

4.4. Limitations

Due to the frustration and discouragement observed when subjects were not able to perform the task at given ARDs during pilot experiments, we used an experimental protocol with increasing PSI task difficulty, which was individually adjusted based on initial ability. In principle, the sequential experimental design could have resulted in fatigue effects (leading to more failures in the more difficult conditions later on). This clearly was not the case in OA, and was checked for and not seen in YA (Potocanac et al., 2014). However, a side effect of the sequential presentation was that a learning

effect appeared in OA (see figure 2b, conditions 1 and 2). It seems that, although they initially performed very poorly, with more training our OA might be able to perform the PSI task at more difficult levels, perhaps even comparable to the YA. This was in hindsight a major limitation, as the protocol we followed worked very well in determining the ARDs at which YA show a dramatic increase of failures, from 15.5% in the ST to a maximum of 80.8% during DT (Potocanac et al., 2014). Because of this learning effect we cannot address the magnitude of age related deterioration in PSI task performance. However, we interpreted our data with due caution and believe the learning effect does not affect the proposed conclusions. Future research could possibly use constant ARD values in order to address this issue (although determining ARD values that could be used for all subjects in both groups will be a challenge).

Secondly, in our experiment the Stroop task stimuli were presented continuously, but were not synchronized to the obstacle presentation in the PSI task. Given the number of Stroop stimuli (several hundred per condition) and the fact that congruent and incongruent stimuli were randomized and counterbalanced, we believe this has no effect on our results. Future research could benefit from synchronizing the Stroop stimuli to obstacle presentation (see e.g. Hegeman et al., 2012), as this would enable assessment of possible congruence effects on different phases of the precision step inhibition.

5. Conclusions

OA were able to perform the PSI walking task, but their performance was worse than previously reported performance of YA. The combination of PSI and Stroop tasks was successful in eliciting DT interference in both YA and OA, probably because it was more demanding than previously used tasks. This DT interference confirmed that the PSI walking task stressed inhibitory requirements in YA, as the Stroop task, when requiring inhibition, affected the rate of incorrect responses during the PSI task, but not during baseline cued walking. Furthermore, Stroop task performance confirmed that OA have difficulties with inhibition, which is in line with experiments on hand function. Finally, we can conclude that OA are able to inhibit their responses on both tasks, but that, unlike YA, they prefer a “posture first strategy” when combining a PSI motor task with a DT.

Acknowledgements

It is a pleasure to thank Bart Nienhuis, for providing the dual task audio files. This research was funded by the European Commission through MOVE-AGE, an Erasmus Mundus Joint Doctorate program (2011-0015). JD has been funded by F.W.O. grant (G.0901.11) and by the Interuniversity Attraction Poles Program initiated by the Belgian Science Policy Office (P7/11).

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Table 1. Average step lengths and individually determined „easiest“ level ARD values for OA and YA. Step lengths were calculated from recorded reflective marker data as half of the distance between two consecutive left heel strikes and averaged for each subject. The data for YA have been reported in (Potocanac et al., 2014).

	average	SD	min	max
<i>step length [m]</i>				
OA	0.48	0.03	0.43	0.53
YA	0.53	0.02	0.50	0.58
<i>"easiest" ARD [mm]</i>				
OA	654.55	15.08	650	700
YA	520.83	51.87	450	600

Table 2. Conversion between the available response distance (ARD) and available response time (ART).

The ART corresponding to each ARD is calculated as $ART\ (ms) = ARD\ (mm) / 0.83$, as our subjects walked at a constant speed of 0.83 m/s. It should be noted that the technical setup manipulated ARD and allowed for variability in the precise position of the stepping stone at the instant of color change. ARD defined the minimal distance from the subject’s center of pressure to the stepping stone that was about to change color, while the maximal possible distance could be ‘ARD + step length’. Therefore, the actual ARDs could be slightly longer, depending on the subject’s step length.

ARD (mm)	300	350	400	450	500	550	600	650	700
ART (ms)	360	420	480	540	600	660	720	780	840

Fig. 1. Experimental setup and conditions. Subjects walked on a system comprising a projector and an instrumented treadmill with stepping stones projected relative to subjects' gait (a). Subjects were instructed to walk by stepping on the stones (b), unless a stone changed color during approach (c). In the latter case the stepping stone represented an obstacle and subjects were instructed to avoid by either shortening or lengthening their step (d). The timing of color changes was random and the position of the stone to color was defined by the available response distance (ARD). ARD was defined as the distance between subject's center of pressure and a virtual threshold in front of the subject (c) and the first stepping stone ahead of this threshold changed color. With permission, reprinted from (Potocanac et al., 2014).

Fig. 2. Average failure rates per individually determined available response distances (2a) and conditions (2b), for OA and YA. Lower available response distances indicate higher task difficulty. Condition 1 is the easiest and the difficulty is increasing in subsequent conditions. Error bars denote standard deviations. See text (section 3.1) for statistical details.

Fig. 3. Stroop composite scores, combining speed and accuracy of responses, for congruent and incongruent stimuli for OA and YA. This score is calculated as rate of correct responses (%) divided by average latency of correct responses (s). A low score indicates poor performance. Error bars denote standard deviations. See text (section 3.2.1) for statistical details.

Fig. 4. Performance on the auditory Stroop task. Rates of correct (4a), incorrect (4b) and omitted responses (4c) and latencies of correct responses (4d) are shown for responses to congruent and incongruent stimuli separately for OA and YA. Error bars denote standard deviations. See text (section 3.2) for statistical details.

a

b CUED WALKING

c COLOR CHANGE (right side)

d OBSTACLE AVOIDANCE (right side)