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Perceptual-motor recalibration is intact in older adults

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A R T I C L E I N F O

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A B S T R A C T

From an ecological perspective, perceptual-motor recalibration should be a robust and adaptable process, but there are suggestions that older adults may recalibrate slower. Therefore, this study investigated the age-related temporal effects in perceptual-motor recalibration after motor disturbances. In three experiments, we disturbed young and older adults' perception-action by fitting weights around their ankles and asking them to climb stairs or cross obstacles repeatedly. In Experiment 1, participants ($n = 26$) climbed stairs with different ankle weights. An innovative methodology was applied, identifying the timeline of recalibration as the point where a stable movement pattern emerged. Experiment 1 showed that older adults recalibrated slower than young adults in lighter (but not heavier) weight conditions. In Experiment 2, participants ($n = 24$) crossed obstacles with different ankle weights. Results showed that older adults recalibrated faster than young adults. Finally, in Experiment 3, participants ($n = 24$) crossed obstacles of unpredictable and varying heights with heavy ankle weights. Again, results showed that older adults recalibrated faster than young adults. Taken together these results show that although older adults had reduced muscle strength and flexibility, they recalibrated quickly, especially when the task was more challenging.

Each year about a third of adults aged over 65 years fall and of these falls 32% can be attributed to tripping, stumbling, hitting or bumping into objects or stairs (Robinovitch & Cronin, 1999). Stepping onto surfaces or over obstacles are actions that people frequently perform, and this familiarity suggests that people automatically pick up the right information to safely perform the action. During these day-to-day activities, however, the perception-action system also needs to deal with perceptual-motor disturbances such as fatigue or wearing new shoes. Such disturbances mean older adults take some time "to get used to" those disturbances and until they do, they may risk a tumble or fall. In this study we investigate the time it takes for older adults to recalibrate to disturbances. *Recalibration*, or the rescaling of the perception-action link, is the process that is thought to be necessary to cope with these acute and long-term disturbances to the perceptual-motor system (Franchak, 2017; Withagen & Michaels, 2004, 2007). Research has shown that young adults can quickly recalibrate to disturbances in their action capabilities (see Brand & de Oliveira, 2017 for a review), but this is unknown for older adults. Therefore, the aim of this study is to test whether there are age-related temporal effects in the recalibration to action disturbances.

The theoretical perspectives used to investigate recalibration or adaptation to disturbances in older adults have been grounded on either cognitive or biomechanical disciplines and these studies found that older adults recalibrated slower to disturbances (Bierbaum, Peper, Karamanidis, & Arampatzis, 2011; Fernández-Ruiz, Hall, Vergara, & Diaz, 2000; McCrum et al., 2016). In walking studies, a slower recalibration has been related with age-related degeneration of the cerebellum (Bruijn, Van Impe, Duysens, & Swinnen, 2012;

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Seidler, 2007). However, these studies either focussed solely on walking or did not incorporate the strong relationship between perception and action. A recent study has found that despite cerebellar degeneration and declines in motor adaptation, recalibration itself was intact or even improved in older adults (Vandevoorde & De Xivry, 2019). These authors systematically tested three reasons for age-related decline in adaptation using reaching movements. They found that cerebellar-based mechanisms appear intact in older adults. It is suggested that an improvement in recalibration with ageing may demonstrate an interplay between different brain regions, where one region could compensate for declines in other regions (Vandevoorde & De Xivry, 2019). The experiments that follow are intended to investigate the robustness of the perceptual-motor system after a disturbance and whether it can deal with both disturbances and the motor declines that come with age.

In this study we take an ecological psychology perspective to perception and action (Gibson, 1979). Previous studies have mainly used judgements to study recalibration of affordance perception (Bingham & Pagano, 1998; Franchak & Adolph, 2014; Mark, Balliett, Craver, Douglas, & Fox, 1990; Stoffregen, Yang, Giveans, Flanagan, & Bardy, 2009; Wagman & Abney, 2012; Yu & Stoffregen, 2012). *Affordances* are the behavioural possibilities in a certain environment for a particular person (Gibson, 1979). It was found that although many affordances can be recalibrated by exploring the relevant perceptual information about the new action boundaries, some other affordances need information on whether or not the action is possible in order to recalibrate successfully (Franchak, 2017; Franchak & Somoano, 2018; Labinger, Monson, & Franchak, 2018). Especially in testing older populations, it is not always feasible to ask them to repeatedly perform actions around their action boundaries. Alternatively, studies can measure recalibration to a disturbance in participants' action capabilities in everyday activities, which also provides more insight into the process of recalibration with practical significance. In these non-maximal everyday tasks, the perception of action-scaled affordances is important because the limits on participants' capabilities to step onto, run, or turn, place critical constraints on successful performance (Fajen, Riley, & Turvey, 2009). Thus, for a successful performance, participants move in such a way that the action is still possible. Fajen and colleagues referred to this as the affordance-based control framework and proposed that people move in such a way that the ideal state does not cross their action boundary (Fajen, 2005, 2007).

Until now only two studies have used kinematic measures to investigate recalibration (Scott & Gray, 2010; Van Hedel & Dietz, 2004). Van Hedel and Dietz (2004) disturbed young adults' obstacle crossing on a treadmill by fitting an ankle-foot, knee, or knee-ankle-foot orthosis on their left leg. They measured leg muscle activity, swing phase duration and toe clearance to investigate recalibration. Results showed that after 50 trials, only participants with the (least restrictive) ankle-foot orthosis had recalibrated. Similarly, Scott and Gray (2010) asked participants to hit balls using differently weighted baseball bats and measured temporal swing error, swing onset time, and bat velocity to investigate recalibration. Their results showed that participants recalibrated their swing accuracy to a heavier bat within ten trials by altering their swing on-set time, whereas the lighter bat group recalibrated their swing accuracy within five trials by changing their swing velocity.

As research has shown that older adults are likely to trip over raised surfaces and loose items on the floor (Lundebjerg, 2001; Startzell, Owens, Mulfinger, & Cavanagh, 2000), we used stair climbing and obstacle crossing as our everyday tasks. These are similar tasks in the sense that both require people to raise their leading foot (onto the first step or over the obstacle) and shift their centre of gravity towards that foot. In stair climbing, people then pull themselves up and carry the trailing foot forward to the next step, whereas in obstacle crossing people swing their trailing foot over the obstacle. In both tasks, the risk of stumbling arises from the possible contact of the leading foot with the stairs/obstacle in the swing phase. An important performance measure in both tasks is toe clearance because a smaller safety margin to clear the step can result in tripping and might lead to falls (Austin, Garrett, & Bohannon, 1999; Begg & Sparrow, 2000; Chen, Lu, Wang, & Huang, 2008; Chou & Draganich, 1997; Elliott, Vale, Whitaker, & Buckley, 2009). Falls could also arise from instability and loss of balance (Austin et al., 1999). Studies have shown that older adults tend to have a longer swing time than young adults during stair climbing and obstacle crossing (Begg & Sparrow, 2000; Benedetti, Berti, Maselli, Mariani, & Giannini, 2007; Chen et al., 2008; Pan, Hsu, Chang, Renn, & Wu, 2016).

Previously, some studies reported on the time course of recalibration by indicating that participants had recalibrated after performing the task a number of times (Bingham & Romack, 1999; Bruggeman, Pick, & Rieser, 2005; Scott & Gray, 2010). For example, Bruggeman et al. (2005) found that participants throwing beanbags while rotating on a carousel recalibrated after two blocks of 5 throws. Although these studies give an estimated range of time needed for recalibration, knowing when participants reach complete recalibration (i.e., the point of recalibration) on a particular task is important because it provides better accuracy allowing for group and condition comparisons. Recently a few studies have identified a timeframe for recalibration, by visually inspecting the data (Day et al., 2019; Franchak & Somoano, 2018; Wang & Bingham, 2019) but here we propose a new method of doing so. Importantly, we consider recalibration as the return to a stable behaviour (following a disturbance) but not necessarily a return to a baseline behaviour.

In a series of three experiments, we examined the trial-by-trial recalibration in young and older adults using tasks that are increasingly demanding from experiments 1 to 3. In the first experiment, we applied disturbances of different magnitude to investigate whether the disturbance magnitude influences the time course of recalibration in stair climbing. In the second experiment, we used obstacle crossing to test whether the same effects were visible in a different and somewhat more demanding task. In the third experiment, we used obstacles of unpredictable height to further increase task demands. Literature has shown that older adults recalibrate slower to a perceptual disturbance (Fernández-Ruiz et al., 2000); therefore, we hypothesised that older adults recalibrate slower than young adults to action disturbances. Literature has also shown that larger disturbances require longer rearrangement periods and therefore we expected to find this effect in both age groups. In exploring task characteristics, we considered that more demanding tasks impose harder constraints on the perceptual-motor system and therefore recalibration to disturbances might take longer in older adults because there might be declines in their perceptual-motor system. On the other hand, more demanding tasks may be riskier for older adults, and this pressure on the perceptual-motor system may speed up recalibration.

Table 1
Mean and SD of participants' characteristics and their action capabilities.

Variables (units)	Young	Older
Age (years)	25.0 ± 5.4	70.3 ± 3.8***
Height (m)	1.75 ± 0.11	1.63 ± 0.06**
Weight (kg)	77.0 ± 16.2	63.9 ± 19.2
Knee extensor muscle strength (N)	478 ± 194	275 ± 49.8**
Hip flexibility (degrees)	64.0 ± 12.3	82.6 ± 14.3**

Note. Significant differences between older and young groups are indicated by ** $p < .01$ ***$p < .001$. The older group showed less strength and flexibility than the young group.

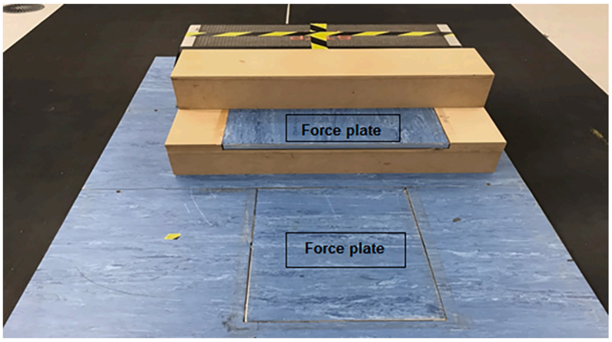

Fig. 1. A photo of the two-step staircase apparatus including two force plates, one mounted on the floor and one on the first step of the staircase. The riser height for each step was 180 mm.

1. Experiment 1

This experiment investigated how long young and older adults take to recalibrate to disturbances of different magnitudes while climbing stairs. We predicted that older adults need to perform more trials than the young adults before they recalibrate (Bierbaum et al., 2011; Bruijn et al., 2012; Fernández-Ruiz et al., 2000; McCrum et al., 2016). In addition, we expected this effect to be more pronounced for larger disturbances (Durgin et al., 2005; Van Hedel & Dietz, 2004).

1.1. Methods

1.1.1. Participants

A total of 26 participants consisting of 14 young adults ($M = 25.0$, $SD = 5.4$ years; 9 females) and 12 older adults ($M = 70.3$, $SD = 3.8$ years; 9 females) volunteered to participate in the experiment (although 30 participants were tested, four were excluded due to poor quality of the motion capture data). The young and older group were significantly different in age, height, knee extensor muscle strength, and hip flexibility (Table 1). The older group were shorter than the young group, which may have made the task harder for them, but well within their action capabilities. The sample size was informed by previous studies (Begg & Sparrow, 2000; Mark et al., 1990; Scott & Gray, 2010; Snapp-Childs & Bingham, 2009). A sample-size estimation based on Begg and Sparrow (2000), who measured differences in step ascent between young and older adults (difference in vertical clearance in two groups of six participants $d = 1.18$), showed that a sample size of two groups of 13 participants would have a power of 0.8. Participants included were healthy, had a self-reported normal or corrected-to-normal vision, and were able to perform the Timed Up and Go Test within 13.5 s showing good mobility (Podsiadlo & Richardson, 1991). Procedures were approved by the University's ethics committee (SAS1715), and the research protocol was carried out in accordance with the Declaration of Helsinki.

1.1.2. Apparatus

A two-step staircase was designed according to standard guidelines for stair construction (Roys, 2001, see Fig. 1). The set-up also included two force plates (9281E, Kistler Instruments Ltd., UK); the first was placed directly in front of the staircase, and the second force plate was mounted into the first step. A stack of gym steps was placed behind the staircase for safety when participants turned around to walk down the stairs.

1.1.3. Procedure

When participants arrived at the lab, the procedures were explained, and consent was obtained. Participants' knee extensor muscle strength, hip flexibility, height, and weight were measured to characterise individual action capabilities. To measure knee extensor muscle strength, three maximum isometric voluntary contractions (MVC) were performed for each leg on an isokinetic dynamometer chair system while participants' hip and knee joints were fixed at a 90° angle (Kin-Com, Chattanoga Group, Inc., TN, USA). Each

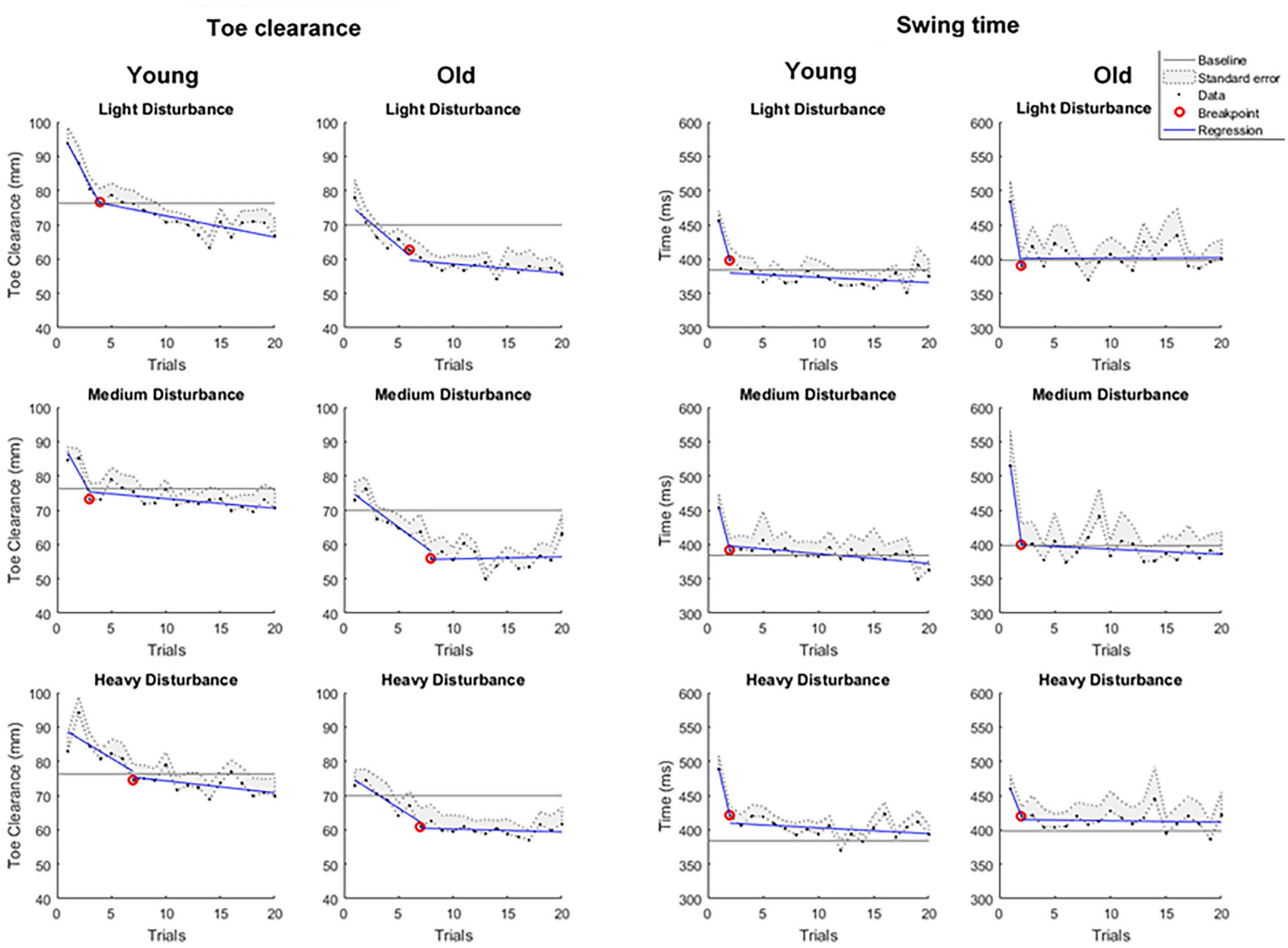

Fig. 2. An outline of recalibration for both groups in toe clearance and swing time of the leading leg. Shaded areas represent the positive standard error of the mean. The two blue lines on each panel show the piecewise regression whose slopes were used to determine whether a stable pattern was achieved. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

participant was instructed to perform an MVC during knee extension for 3 s with 1-min rest in between each of the MVCs (Konczak, Meeuwsen, & Cress, 1992). Individual knee extensor muscle strength was measured as the peak knee extensor muscle strength per leg (in Newtons). To measure hip flexibility, participants were asked to raise their leg three times as high as possible while standing unsupported. Reflective markers for motion capture were placed on the shoulder (acromion), hip (greater trochanter) and knee (lateral epicondyle) to measure hip flexibility, and calculated as the minimum trunk-thigh angle during active flexion in an upright position for each leg (Konczak et al., 1992).

Markers were then placed on participants' lower body and individual stepping actions were recorded using 3D motion capture (Qualisys AB, Sweden). A lower-limb model was defined by placing 40 reflective markers which included 26 tracking markers (Jones, James, Thacker, & Green, 2016; Ren, Jones, & Howard, 2008). All markers were used to model the lower-body in the static trial in which participants were asked to hold the anatomical position to take a 5-s capture. The static markers were then removed and only the tracking markers were used for the subsequent movement trials. Marker data were recorded using eight infrared cameras sampled at 100 Hz and synchronously recorded with the analogue input from the two force plates at 1000 Hz (9281E, Kistler Instruments Ltd., UK).

For the task, participants were instructed to start with both feet on the first force plate and to climb the staircase, stop, turn around and climb down (a step-over-step pattern was demonstrated). First, participants were asked to climb the staircase five times without any ankle weights (*baseline*). They were fitted with ankle weights (*light, medium, or heavy disturbance*) and asked to climb the staircase again for 20 consecutive trials. Then the ankle weights were removed and participants were asked to walk back and forth along a 15 m area for about 3 min to ensure that the effects of the weight condition were no longer present (i.e., post-recalibration). The second set of weights was then fitted and the procedure repeated, followed by the last set of weights. The three weight conditions were counterbalanced between participants. The weights were calculated as a percentage of the individual peak knee extensor muscle strength to control for differences in leg strength between the age-groups (Nessler, Gutierrez, Werner, & Punsalan, 2015; Ramenzoni, Riley, Shockley, & Davis, 2008). The three weight conditions were light (1.25% of MVC), medium (2.5% of MVC) and heavy (5% of MVC).

1.1.4. Analysis

Step pattern was analysed from the toe-off of the leading foot in the starting position until it landed on the first step. Similar to Pijnappels, Bobbert, and Van Dieën (2001), toe-off was detected from the kinematic data as the maximum vertical velocity of the leading foot's calcaneus marker. The landing was determined from the data of the force plate mounted on the first step; the first frame where the vertical ground reaction force was consistently over 20 N determined foot landing (Zeni, Richards, & Higginson, 2008).

Raw marker and analogue data were imported into Visual3D (C-Motion Inc., USA). Marker data was filtered with a 4th-order 6 Hz low-pass Butterworth filter and force plate data was filtered using a 4th-order 25 Hz low-pass Butterworth filter (Alcock, O'Brien, & Vanicek, 2014; Alcock, Vanicek, & O'Brien, 2013; Jones et al., 2016). Data were exported from Visual3D into Matlab 2016b (The MathWorks, Natick, MA, USA) for further analysis. Toe clearance, defined as the maximum vertical distance between the first metatarsal marker and the horizontal surface of the step (Alcock et al., 2013; Pijnappels et al., 2001; Snapp-Childs & Bingham, 2009), was the performance measure calculated from the trajectory of the leading foot. We also calculated swing time, defined as the difference in time between toe-off and landing of the leading foot on the first step (Benedetti et al., 2007; Sparrow & Tirosh, 2005).

To determine whether recalibration occurred, we first fitted a piecewise regression over trials 1 to 20 for each group and condition. This regression analysis method, which has not been applied to recalibration before, partitioned the data into two intervals and fitted a separate regression to each interval (cf., Sleimen-Malkoun, Temprado, Huys, Jirsa, & Berton, 2012). The boundary between the two intervals is known as breakpoint. To calculate the regression slopes, we fitted two regressions to the data of each participant and condition using the breakpoint previously found for the group. For example, if the breakpoint in the light weight condition for young adults was identified at trial 7, then linear regressions were fitted over trials 1–7 and trials 7–20 for each participant in that group/condition. The piecewise regression method was applied to each of the kinematic variables. The slopes of the two individual regressions were submitted to a two-way mixed ANOVA with within-subjects factors Time (2 levels: initial vs final), Condition (3 levels: light vs medium vs heavy weights), and between-subjects factor Group (2 levels: young vs older group). Homogeneity of variance was confirmed using the Levene's test. Where a violation of sphericity was found in the Mauchly's test, a Greenhouse-Geisser correction was applied. Post-hoc tests with Least Significant Difference (LSD) correction were applied on significant main effects. When the analysis showed an effect of recalibration (i.e., a main effect of time) the *point of recalibration* was recorded as the breakpoint found in the piecewise regression. Throughout the analysis of the results, a significance level (alpha) of 5% was used. All statistical data were analysed using SPSS 21.0.

1.2. Results

In this section, the results for each kinematic variable will be presented in regards to recalibration effects (main effects of time). Where recalibration effects are found, we also present data on the point of recalibration.

1.2.1. Toe clearance

Regarding recalibration, results showed a main effect of time, $F(1,22) = 18.5$, $p < .001$, $\eta^2 = 0.839$, because the initial rearrangement slope ($M = -3.57$, $SE = 0.749$) was steeper than the final slope ($M = -0.225$, $SE = 0.074$, see Fig. 2). There was no main effect of weight, $F(2, 44) = 2.13$, $p = .131$, $\eta^2 = 0.098$, and no significant group effect, $F(1,22) = 2.41$, $p = .135$, $\eta^2 = 0.109$. No interaction effects were found (all $F < 1.50$, $p > .100$). Upon visual inspection, the slopes of the younger adults indicated potential incomplete recalibration. A one-sided t-test against 0 confirmed that this was only the case for the light condition, $t(13) = 3.965$, $p =$

Table 2
Mean and SD of participants' characteristics and their action capabilities.

Variables (units)	Young	Older
Age (years)	27.67 ± 5.40	70.75 ± 6.12***
Height (m)	1.74 ± 1.39	1.68 ± 4.83
Weight (kg)	71.7 ± 12.4	69.7 ± 15.6
Knee extensor muscle strength (N)	461 ± 139	271 ± 89.2**
Hip flexibility (degrees)	69.8 ± 13.6	86.8 ± 11.9**

Note. Significant differences between older and young groups are indicated by ** $p < .01$ ***$p < .001$. The older group showed less strength and flexibility than the young group.

.002. For all other conditions and groups, the second slope was not statistically different from 0.

Regarding the point of recalibration, the breakpoint analysis showed that while young adults recalibrated within 3–4 trials for the light and medium weight conditions and 7 trials in the heavy weight condition, older adults took between 6 and 8 trials to recalibrate in all weight conditions (see Fig. 2).

1.2.2. Swing time

Regarding recalibration, results showed a main effect of time, $F(1,21) = 28.3, p < .001, \eta^2 = 1.36$, because the initial rearrangement slope ($M = -0.058$, $SE = 0.011$) was steeper than the final slope ($M < 0.001$, $SE < 0.001$). There were no main effects of condition, $F(2, 42) = 2.19, p = .125, \eta^2 = 0.107$, or group, $F(1,21) = 0.234, p = .634, \eta^2 = 0.013$. Results showed no Condition × Group interaction, $F(2, 42) = 2.83, p = .070, \eta^2 = 0.139$, and no Condition × Time × Group interaction, $F(2, 42) = 2.75, p = .075, \eta^2 = 0.133$. No other significant interactions were found (all $F < 3.00, p > .05$).

Regarding the point of recalibration, the breakpoint analysis showed that both groups recalibrated within 2 trials across all weight conditions (see Fig. 2).

1.3. Discussion

This experiment investigated how many trials young and older adults take to recalibrate to disturbances of different magnitudes while climbing stairs. Results showed that older adults took a few extra trials to recalibrate their toe clearance compared to young adults (6–8 versus 3–7 trials across weight conditions). This was expected (cf., Bierbaum et al., 2011; Fernández-Ruiz et al., 2000; McCrum et al., 2016). However, older adults did not recalibrate faster to smaller disturbances and slower to larger disturbances as was expected (Durgin et al., 2005; Fernández-Ruiz & Díaz, 1999; Van Hedel & Dietz, 2004; and as the younger adults did). Instead, they used a similar amount of trials for all disturbance magnitudes. This could indicate that older adults overcompensated the initial rearrangement for smaller disturbances. Older adults have been shown to respond to smaller perturbations more than young adults and were more likely to use an extra step to recover their balance after a moving platform was used to disturb their balance (Jensen, Brown, & Woollacott, 2001; Maki, Edmondstone, & McIlroy, 2000). Older adults may have used the overcompensation as a safety mechanism after lighter disturbances, which ultimately led to a similar recalibration across disturbances. Being aware of the weights attached to their ankles, participants may have made an effort to maintain or slightly raise their toe clearance but were not able to increase toe clearance as much as young adults due to reduced action capabilities (cf., Chiou, Turner, Zwiener, Weaver, & Haskell, 2012; Johnson, Buckley, Scally, & Elliott, 2007).

2. Experiment 2

In this experiment, we were interested to see whether the results of stair climbing in Experiment 1 applied also to the more demanding task of obstacle crossing. In exploring task characteristics, we considered that more demanding tasks impose harder constraints on the perceptual-motor system, and therefore recalibration to disturbances might take longer in older adults if there were declines in their perceptual-motor system (Bierbaum et al., 2011; Bruijn et al., 2012; Fernández-Ruiz et al., 2000; McCrum et al., 2016). On the other hand, given the result of Experiment 1, more demanding tasks may be riskier for older adults, and this pressure on the perceptual-motor system may speed up recalibration.

2.1. Methods

2.1.1. Participants

A total of 24 participants consisting of 12 young adults ($M = 27.7$, $SD = 5.40$ years; 5 females) and 12 older adults ($M = 70.8$, $SD = 6.12$ years; 7 females) volunteered to participate in this experiment (each experiment had a newly recruited cohort of participants). The young and older group were significantly different in age, height, knee extensor muscle strength, and hip flexibility (see Table 2). Experiments 2 and 3 received University ethics approval (SAS1805).

2.1.2. Apparatus

The obstacle was a long wooden plank measuring 80 × 750 × 20 mm attached to the top of a mechanical device and set at a fixed

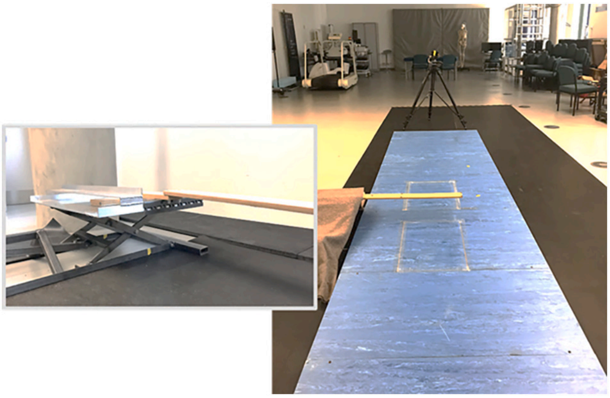

Fig. 3. A photo of the obstacle apparatus and set-up. The setup consisted of the obstacle apparatus set halfway on a runway between two force-plates. The apparatus consisted of a mechanical device with adjustable height and an obstacle add-on. The obstacle apparatus was covered during experiments (photo on the right) but is visible on the left.

height of 130 mm (see Fig. 3). Four markers were attached to the obstacle monitoring its position in space. The obstacle was positioned in the middle of a runway with a tripod on either end of the runway. Force plates (9281E, Kistler Instruments Ltd., UK) were placed on either side of the obstacle, so participants stepped on them before and after crossing the obstacle.

2.1.3. Procedure

The procedure was similar to Experiment 1. Participants' step pattern was measured, using markers on their feet, as they walked and crossed the obstacle. Participants were instructed that the task was to walk from one end of the runway to the other to touch a button on the tripod, crossing the obstacle when they encountered it. Touching the button served the sole purpose of directing participants' attention away from the obstacle. In the first condition (*baseline*), participants were asked to cross the obstacle for 30 trials without any ankle weights. In the second and third condition which were counterbalanced (*light and heavy disturbance*), participants were asked to perform 30 trials while wearing light and heavy ankle weights (1.25 and 5% of MVC in Newtons). Between the two disturbance conditions, participants were asked to walk back and forth along a 15 m area for about 3 min to ensure that the effects of the weights were no longer present (i.e., post-recalibration). Participants were asked instructed not to move or sway after having weights fitted around their ankles until they were allowed to walk and cross the obstacle.

2.1.4. Analysis

The step pattern was analysed from toe-off of the leading foot on one side of the obstacle to the landing of the leading foot on the other side of the obstacle. Exact obstacle height was derived from the two markers positioned on the side participants approached it. The same kinematic measures were used as for Experiment 1.

Unlike Experiment 1, we asked participants to complete an extensive amount of baseline trials to confirm that no changes occurred during baseline. Linear regressions were fitted over 30 baseline trials for each participant and slopes were submitted to a two-way mixed ANOVA with within-subjects factors Time (2 levels: initial vs final), Condition (2 levels: light vs heavy weights), and between-subjects factor Group (2 levels: young vs older group).

2.2. Results

In this section, the results for each kinematic variable will be presented regarding the recalibration effects during the light and heavy weight conditions. Where recalibration effects are found, we also present data on the point of recalibration.

2.2.1. Toe clearance

Regarding recalibration, results showed a main effect of time, $F(1, 22) = 4.38$, $p = .048$, $\eta^2 = 0.199$, because the initial rearrangement slope ($M = -7.48$, $SE = 3.42$) was steeper than the final slope ($M = -0.255$, $SE = 0.122$, see Fig. 4). There was no main effect of condition, $F(1, 22) = 2.37$, $p = .138$, $\eta^2 = 0.099$. There was no significant group effect, $F(1, 22) = 0.078$, $p = .782$, $\eta^2 = 0.004$, and no interactions (all $F < 2.50$, $p > .150$). Fig. 4 shows a shallow initial slope in the young group for the heavy weight, which an additional t-test showed was not significantly different from the final slope, $t(11) = 1.537$, $p = .152$, $d = 0.708$.

Regarding the point of recalibration, the breakpoint analysis in the light weight condition showed that both groups recalibrated within 2 trials. In the heavy weight condition, the older adults recalibrated within 6 trials, but the young adults did not fully recalibrate (see Fig. 4).

2.2.2. Swing time

Regarding recalibration, there was no significant time effect, $F(1, 22) = 2.10$, $p = .161$, $\eta^2 = 0.103$ (see Fig. 4). In addition, no main

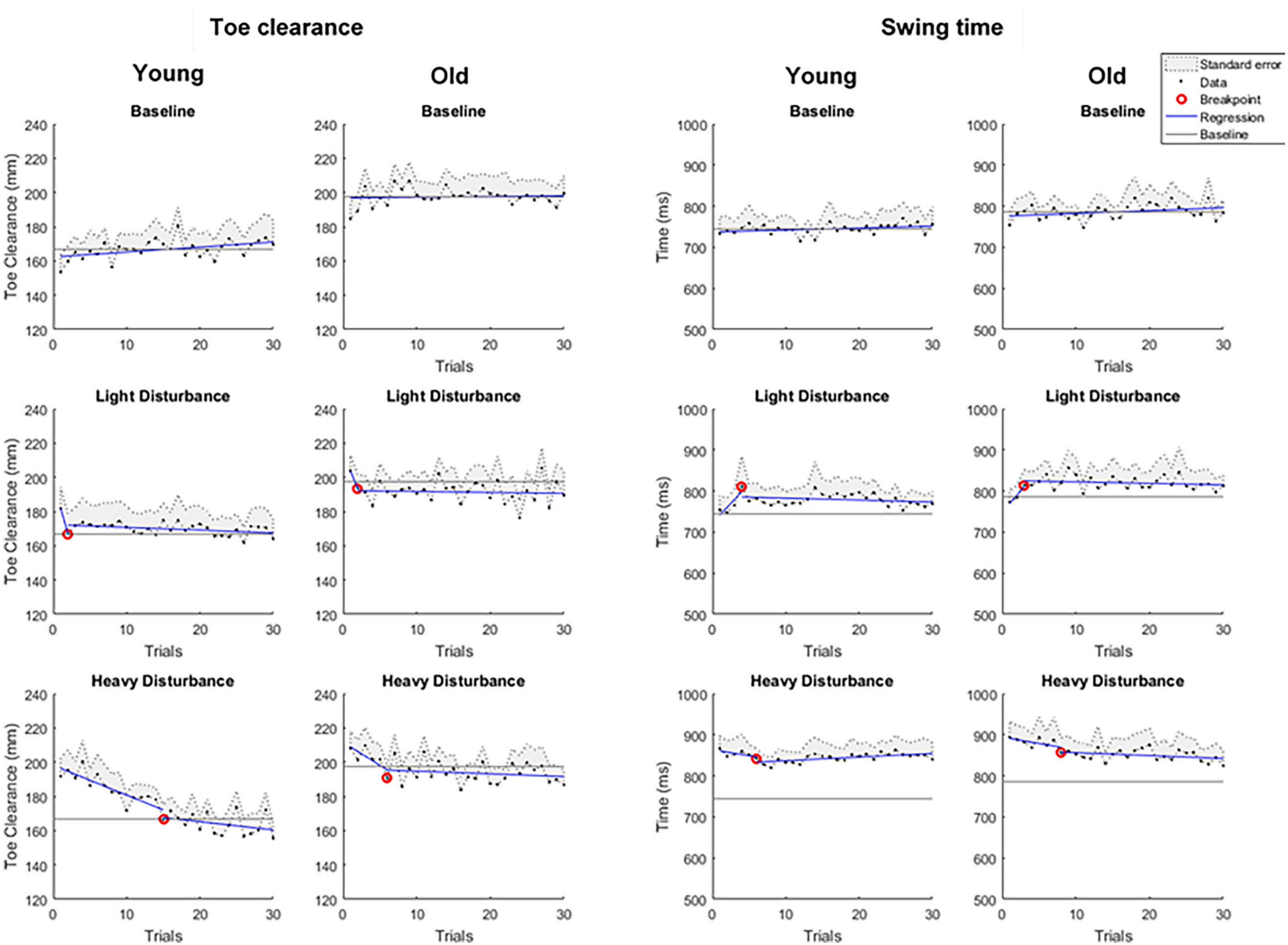

Fig. 4. An outline of recalibration for both groups in toe clearance and swing time of the leading leg. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > .05$).

Table 3
Mean and SD of participants' characteristics and their action capabilities.

Variables (units)	Young	Older
Age (years)	28.9 ± 6.2	71.6 ± 4.0***
Height (m)	1.69 ± 0.10	1.65 ± 0.06
Weight (kg)	68.1 ± 11.2	70.2 ± 18.0
Knee extensor muscle strength (N)	437 ± 139	312 ± 77.5*
Hip flexibility (degrees)	69.9 ± 9.5	86.6 ± 13.9**

Note. Significant differences between young and older groups are indicated by *$p < .05$, **$p < .01$ or ***$p < .001$. The older group showed less strength and flexibility than the young group.

effect of condition and group were found (respectively, $F(1, 22) = 1.99$, $p = .172$, $\eta^2 = 0.111$; $F(1, 22) = 0.847$, $p = .367$, $\eta^2 < 0.036$). No other interaction effects were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis in light weight condition showed that the older adults recalibrated within 3 trials. No recalibration occurred in the other weight/group conditions (see Fig. 4).

2.3. Discussion

This experiment investigated how many trials young and older adults take to recalibrate to disturbances of different magnitudes when crossing an obstacle. Surprisingly, results showed that while young adults were still recalibrating after 15 trials in the heavy weight condition, older adults recalibrated within 6 trials. For the light weight condition, both groups recalibrated within 2 trials. Both groups recalibrated faster after smaller disturbances and slower after larger disturbances as would be expected.

Results suggest there is no general perceptual-motor decline in older adults, but instead, that the time course of recalibration is related to the characteristics of the task. A faster recalibration to the heavy weights in older adults may have resulted from increased pressure on their perceptual-motor system to recalibrate. Pressures would be their reduced action capabilities (ie., less strength and flexibility; cf. Nigam, Knight, Bhattacharya, & Bayer, 2012) and the perceived consequences of tripping on the obstacle (Austin et al., 1999). Typically, the perceptual-motor system does not strive for optimisation but rather uses good-enough strategies in response to pressure (e.g., Bobbert, Richard Casius, & Kistemaker, 2013; De Oliveira, Billington, & Wann, 2014; de Oliveira, Raab, Hegele, & Schorer, 2017;Raab, de Oliveira, Schorer, & Hegele, 2013) so the recalibration may have taken fewer attempts when it was more important to do so. In addition, it could also be that older adults explored and performed actions closer to their maximal action capabilities (cf., Fajen et al., 2009), which may have led to a faster recalibration.

3. Experiment 3

This experiment investigates age-related differences in the time course of recalibration in an unpredictable environment (i.e., when crossing obstacles of varying height; cf. Lundebjerg, 2001). Research has shown that older adults tend to use conservative strategies when crossing obstacles in unpredictable environments resulting in longer movements and higher toe clearance (Caetano et al., 2016; Lu, Chen, & Chen, 2006; Patla & Rietdyk, 1993; Shin et al., 2015; Yen, Chen, Liu, Liu, & Lu, 2009). However, following the results of Experiment 2 we predicted that older adults recalibrate faster than young adults in this demanding task.

One feature of the recalibration process that was discussed in the literature but has not been addressed so far is the disturbance removal. Several studies showed recalibration as an *aftereffect* following the removal of the disturbance (Bruggeman et al., 2005; Rieser, Pick, Ashmead, & Garing, 1995; Withagen & Michaels, 2007). After the removal of a disturbance, a new rearrangement period occurs in which participants get used to their new capabilities and usually recalibrate back to baseline (Brand & de Oliveira, 2017). Studies have shown that aftereffects are similar for both young and older adults (McCrum et al., 2016; Vervoort et al., 2019) so in this experiment, we expected to see a similar time course of aftereffects for both groups.

3.1. Methods

3.1.1. Participants

A total of 24 participants consisting of 12 young ($M = 28.9$, $SD = 6.2$ years; 8 females) and 12 older adults ($M = 71.6$, $SD = 4.0$ years; 7 females) volunteered to participate in the experiment. The young and older group were significantly different in age, knee extensor muscle strength, and hip flexibility (Table 3).

3.1.2. Apparatus

We used the same obstacle as in Experiment 2 and varied its height between 90 and 180 mm using an electrical controller attached to a scissor jack (see Fig. 3).

3.1.3. Procedure and analysis

In this experiment only the heavy weight condition was used. Participants' step pattern was measured while they walked and crossed an obstacle of varying heights. Participants were asked to wait at the end of the catwalk while the experimenter changed

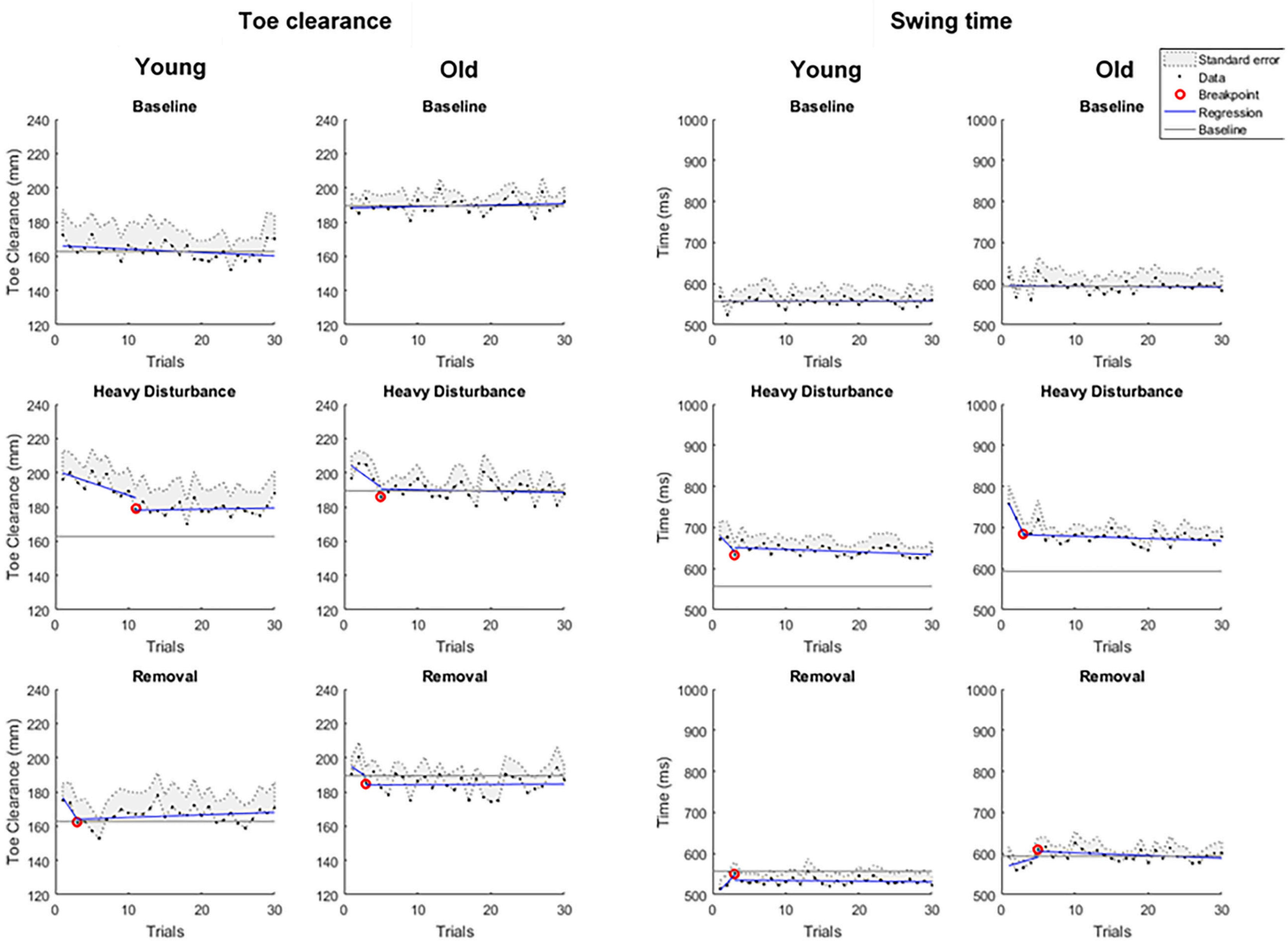

Fig. 5. An outline of recalibration for both groups in toe clearance and swing time. Shaded areas represent the positive standard error of the mean. Baseline slopes were not significantly different from zero ($p > .05$).

obstacle height without participants seeing it. In each condition, heights were pseudo-randomised and presented to the participants in 3 blocks of 10 heights (ranging from 9 to 18 cm). *Baseline was* 30 trials without any ankle weights. *Disturbance* was 30 trials with heavy ankle weights. In the *removal* condition, the ankle weights were removed and participants performed 30 trials. Participants' step pattern was analysed as in experiment 2. The regression slopes were submitted to a two-way mixed ANOVA with within-subjects factors Time (2 levels: initial vs final), Condition (2 levels: heavy weights vs removal), and between-subjects factor Group (2 levels: young vs older group).

3.2. Results

In this section, the results for each kinematic variable will be presented regarding the recalibration effects during the disturbance and removal conditions. Where recalibration effects are found, we also present data on the point of recalibration.

3.2.1. Toe clearance

Regarding recalibration, results showed a main effect of time, $F(1, 22) = 5.26$, $p = .032$, $\eta^2 = 0.239$, because the initial rearrangement slope ($M = -3.35$, $SE = 1.47$) was steeper than the final slope ($M = 0.040$, $SE = 0.130$, see Fig. 5). There was no main effect of condition, $F(1, 22) = 0.787$, $p = .385$, $\eta^2 = 0.036$. There was no significant group effect, $F(1, 22) = 0.031$, $p = .862$, $\eta^2 = 0.001$, and no interactions were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis in the disturbance condition showed that young adults recalibrated within 11 trials and older adults within 5 trials. In the removal condition, both groups recalibrated within 3 trials (see Fig. 5).

3.2.2. Swing time

Regarding recalibration, there was no significant time effect, $F(1, 22) = 2.78$, $p = .110$, $\eta^2 = 0.105$. A main effect of condition was found ($F(1, 22) = 11.903$, $p = .002$, $\eta^2 = 0.545$). There was no significant group effect, $F(1, 22) = 0.957$, $p = .339$, $\eta^2 = 0.053$. There was a Time × Condition interaction, $F(1, 22) = 11.748$, $p = .002$, $\eta^2 = 0.545$, because initial rearrangement slopes for the disturbance condition were negative ($M = -0.033$, $SE = 0.011$), whereas initial slopes for the removal condition were positive ($M = 0.012$, $SE = 0.005$, see Fig. 5). Both conditions had similar slopes for the final rearrangement (Disturbance: $M = -0.001$, $SE < 0.001$; Removal: $M < 0.001$, $SE < 0.001$). Additional *t*-tests between initial and final rearrangement slopes were significantly different in the disturbance and the removal conditions (respectively, $t(23) = 2.88$, $p = .008$, $d = 0.821$, and, $t(23) = 2.40$, $p = .025$, $d = 0.705$), indicating that recalibration occurred in both conditions. No other interaction effects were found (all $F < 1.50$, $p > .100$).

Regarding the point of recalibration, the breakpoint analysis showed that both young and older adults recalibrated within 3 trials in the disturbance condition. In the removal condition, young adults recalibrated within 3 and older adults within 5 trials (see Fig. 5).

3.3. Discussion

Results showed that while young adults took 11 trials to recalibrate after the disturbance, older adults only needed 5 trials. Upon removal of the disturbance, both groups recalibrated within 3 trials. These results further suggest that the temporal effect of recalibration is related to the characteristics of the task. Given that the task demands in crossing an obstacle of varying height were greater for older than young adults (given different action capabilities), this is likely to have placed increased pressure on their perceptual-motor system to recalibrate, resulting in faster recalibration.

In addition, the aftereffects of toe clearance were in the same direction as the initial disturbance effect, whereas for swing time the aftereffects were in the opposite direction to the effects of disturbance. It is possible that, for swing time, the weight disturbance slowed down participants' movements, which upon removal resulted in faster movements. This reversal of direction is similar to previous studies (Fernández-Ruiz et al., 2000; McCrum et al., 2016; Vervoort et al., 2019). The question arises whether aftereffects can also occur in the same direction of the disturbance effect. Our results suggest that this is the case; the disturbance removal is itself another disturbance, albeit one usually followed by a faster rearrangement (Brand & de Oliveira, 2017). It seems that, in obstacle crossing, the principal response to any disturbance (including disturbance removal) is to increase the safety margin, which is accomplished by raising toe clearance (cf., Van Hedel & Dietz, 2004). Further, the aftereffect observed in swing time may have itself provoked a raised toe clearance. Previous studies which found aftereffects in the opposite direction of the disturbance used tasks that had a clear direction of recalibration, for instance using prism glasses (e.g., Fernández-Ruiz et al., 2000; Fernández-Ruiz & Díaz, 1999; Redding & Wallace, 2002). This has led to generalisations about the direction of aftereffects (Brand & de Oliveira, 2017). However, we now propose that the direction of the aftereffect is variable and dependent on the task and disturbance. Future studies should further explore aftereffects of recalibration in different everyday activities.

4. General discussion

One of the main findings of this study was that recalibration seemed to be constrained by task demands and action capabilities. Action capabilities were reduced in older adults as seen in their weaker knee extensor muscle strength and hip flexibility compared with younger adults. The tasks used in the study were more demanding from experiment 1 to experiment 3 (from stair climbing to obstacle crossing to obstacle crossing with varying height) but also within experiments 1 and 2 there were conditions that were more demanding (light versus heavy weight conditions). Within and across experiments we saw older adults using fewer trials to return to a stable pattern of toe clearance when the tasks were more demanding (eg, for the heavy weight condition from experiment 1 to 3 the

Table 4
Summary of the three experiments' methods, main results and conclusions.

	Experiment 1	Experiment 2	Experiment 3
Participants	14 YA 25.0 ± 5.4 years 12 OA 70.3 ± 3.8 years	12 YA 27.7 ± 5.40 years 12 OA 70.8 ± 6.12 years	12 YA 28.9 ± 6.2 years 12 OA 71.6 ± 4.0 years
Task	Two-step staircase 180 mm riser height	Obstacle 130 mm high	Obstacle height ranging 90–180 mm
Disturbance	Light, medium and heavy ankle weights	Light and heavy ankle weights	Heavy ankle weights
Procedure	5 baseline trials, 20 trials per weight condition	30 trials for baseline and weight conditions	30 trials for baseline, weight, removal
Results	Toe Clearance Main effect of time ($F(1, 22) = 18.5$, $p < .001$, $\eta^2 = 0.839$). *Point of recalibration:* YA 3–4 trials for light/ medium weights, 7 trials for heavy weight. OA 6–8 trials for all weights.	Toe Clearance Main effect of time ($F(1, 22) = 4.38$, $p = .048$, $\eta^2 = 0.199$). *Point of recalibration:* YA/OA 2 trials for light weight, YA did not recalibrate to heavy weight, OA 6 trials for heavy weight.	Toe Clearance Main effect of time ($F(1, 22) = 5.26$, $p = .032$, $\eta^2 = 0.239$). *Point of recalibration:* YA 11 trials, OA 3 trials for heavy weight.
Summary conclusion	OA recalibrated slower than YA in lighter but not heavier weight conditions	OA recalibrated faster than YA	OA recalibrated faster than YA

Note. Only significant effects for toe clearance are presented, full results in the text. YA is younger adults and OA is older adults.

older adults needed 7, 6, and 3 trials respectively; see Table 4). This suggests that the perceptual-motor system is robust and capable of dealing with action disturbances even in the face of age-related declines. These results confirm the recent findings that perceptual-motor recalibration was intact or even improved in older adults while cognitive-based adaptation showed deficits (Vandevoorde & De Xivry, 2019).

The recalibration mechanism of older adults may be affected by two aspects: a reduced neuro-behavioural repertoire and an increased risk of fall both of which constrain their perception-action system. Previous studies suggest a compression of the neuro-behavioural repertoire with ageing (Sleimen-Malkoun, Temprado, & Berton, 2013; Sleimen-Malkoun, Temprado, & Hong, 2014; Vernooij, Rao, Berton, Retornaz, & Temprado, 2016). Sleimen-Malkoun et al. (2014) concluded that ageing might also lead to a loss of multi-stability in terms of available movement patterns. If this is the case, a smaller perceptual-motor space with fewer action possibilities might lead to a faster recalibration. This would be visible in older versus younger adults but also in more versus less demanding tasks. An increased risk of falling may also contribute by reducing the action possibilities further. Future research may investigate these mechanisms by manipulating the perceptual-motor space available during recalibration. Theoretically this is important because the results place recalibration in the interaction between the individual and the task constraints (i.e., depending on task constraints recalibration is faster or slower for older adults), rather than simply within the individual (i.e., older adults recalibrate slower or faster than younger adults regardless of task).

This study introduces an important methodological innovation in the study of recalibration. Although the concept of recalibration is clear, its operational definition has been changing (Day et al., 2019). Studies typically reported a reduction in error as indicative that recalibration had taken place (see Brand & de Oliveira, 2017 for a review). Error can be defined as the difference between perceptual and action boundaries (Bruggeman et al., 2005) or as reductions in throwing errors, swing onset errors, and movement times (Scott & Gray, 2010). Our results suggest that recalibration should be operationally defined as the recovery of a stable perceptual-motor pattern. If the task goal is defined as a target to reach, recalibration can be measured as error reduction but will also show the recovery of a stable pattern (cf., Scott & Gray, 2010). If the task goal is a target to avoid (e.g., obstacle), the possibilities for action are broader and error reduction will not be a good measure (also, having a similar toe clearance with and without heavy ankle weights might not be possible or even desirable). The piecewise regression method (cf., Sleimen-Malkoun et al., 2012) applies well to both types of tasks to identify recalibration and uncover its time course. We like to add here that the piecewise regressions resulted in larger coefficients of determination than a linear regression for all groups/conditions except where recalibration seemed to be incomplete (i.e., Exp. 1 young light and Exp. 2 young heavy).

Training could be used to optimise movement patterns while promoting a fast recalibration to disturbances. A good training strategy for coping with perceptual-motor disturbances is to be exposed to them in a controlled environment. Repeated exposure to disturbances followed by recalibration seem to result in faster recalibration and better movement patterns (Brand & de Oliveira, 2017; cf., McCrum et al., 2016). Virtual reality might provide a good training ground given that participants use affordance-based control in virtual everyday tasks (Rybarczyk, Coelho, Cardoso, & de Oliveira, 2014). A training program that includes disturbances in a controlled and safe environment for older adults is a fruitful application of recalibration research.

In conclusion, by examining two everyday activities, we found that both young and older adults recalibrated quickly, but not in the same way. Young adults recalibrated faster than older adults in less demanding tasks, but when faced with more demanding tasks and an unpredictable environment, the older adults recalibrated faster. It seems that the process of recalibration was intact in both groups, but the temporal aspect of recalibration may have been constrained by reduced action capabilities and perceived consequences of the task in the older group.

CRediT authorship contribution statement

Milou T. Brand: Conceptualization, Methodology, Investigation, Visualization. **Rita F. de Oliveira:** Conceptualization, Methodology, Resources, Supervision, Project administration.

Data availability

Data will be made available on request.

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