Exp Brain Res (2017) 235:2391–2405
DOI 10.1007/s00221-017-4975-7

RESEARCH ARTICLE

# Visuotactile interaction even in far sagittal space in older adults with decreased gait and balance functions

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Received: 7 November 2016 / Accepted: 29 April 2017 / Published online: 10 May 2017

**Abstract** Spatial proximity of signals from different sensory modalities is known to be a crucial factor in facilitating efficient multisensory processing in young adults. However, recent studies have demonstrated that older adults exhibit strong visuotactile interactions even when the visual stimuli were presented in a spatially disparate position from a tactile stimulus. This suggests that visuotactile peripersonal space differs between older and younger adults. In the present study, we investigated to what extent peripersonal space expands in the sagittal direction and whether this expansion was linked to the decline in sensorimotor functions in older adults. Vibrotactile stimuli were delivered either to the left or right index finger, while visual stimuli were presented at a distance of 5 cm (near), 37.5 cm (middle), or 70 cm (far) from each finger. The participants had to respond rapidly to a randomized sequence of unimodal (visual or tactile) and simultaneous visuotactile targets (i.e., a redundant target paradigm). Sensorimotor functions were independently assessed by the Timed Up and Go (TUG) and postural stability tests. Results showed that reaction times to the visuotactile bimodal stimuli were significantly faster than those to the unimodal stimuli, irrespective of age group [younger adults: 22.0 ± 0.6 years, older adults: 75.0 ± 3.3 years (mean ± SD)] and target distance. Of importance, a race model analysis revealed that the co-activation model (i.e., visuotactile multisensory integrative process) is supported in the far condition especially for older adults with relatively poor performance on the TUG or postural stability tests. These results suggest that aging can change visuotactile peripersonal space and that it may be closely linked to declines in sensorimotor functions related to gait and balance in older adults.

**Keywords** Aging · Older adults · TUG · Postural stability · Sensorimotor · Visuotactile · Crossmodal interaction · Peripersonal space

## Introduction

Appropriate integration and isolation of information from multisensory modalities is essential for the brain to obtain stable and robust representations of the surrounding world. Most recent studies investigating age differences in multisensory processing have reported that such multisensory integration/isolation processes change with age. In the audiovisual domain, greater multisensory response enhancement has been demonstrated in older adults compared to younger adults in a variety of measures such as: rapid discrimination response to audiovisual multisensory or constituent unisensory targets (Laurienti et al. 2006), simple detection (Peiffer et al. 2007; Mahoney et al. 2011), saccade reaction times (Diederich et al. 2008), susceptibility to double flash illusion (DeLoss et al. 2013; McGovern et al. 2014; Setti et al. 2011), and temporal perception (Bedard and Barnett-Cowan 2016; Brooks et al. 2015; Fiacconi et al. 2013; Noel et al. 2016). Other multisensory pairings provided further evidence that older adults exhibit greater multisensory processing relative to younger adults [vision and touch (Couth et al. 2016; Mahoney et al. 2011; Poliakoff et al. 2006a, b); hearing and touch (Mahoney

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et al. 2011)]. Thus, it appears likely that, compared to young adults, older adults rely more heavily on multisensory information for constructing their perceptual world and guiding their actions.

It is well known that spatial coincidence of signals from different sensory modalities is crucial for efficient multisensory processing along with temporal coincidence and signal weakness (i.e., "inverse effectiveness") (see Spence 2013 for a review). While this spatial rule often governs multisensory phenomena in young adults (especially those in which spatial responses are required), recent studies have proposed that this rule is less applicable to older adults. Poliakoff et al. (2006a) investigated age differences in visuotactile interaction using a crossmodal congruency task (Spence et al. 2004). In this task, the participants held a foam cube in each hand between the thumb and index finger. The vibrotactile stimulators and light emitting diodes (LEDs) were attached close to the fingers. The participants were asked to discriminate the location of a tactile target presented to either the thumb or index finger either on their left or right hand while ignoring a concurrent visual distractor that was also presented randomly from one of four possible locations. In general, visual distractors interfere with tactile discrimination when these stimuli are delivered to incongruent fingers, while visual stimuli facilitate the discrimination performance when these stimuli are delivered to congruent fingers (these are called as crossmodal congruency effects). Young participants exhibited larger crossmodal congruency effects when the visual stimulus was presented close to the stimulated hand rather than to the unstimulated hand on the contralateral side. In contrast, older participants displayed almost equivalent crossmodal congruency effects irrespective of whether the visual distracter was presented on the ipsilateral or contralateral side. Similarly, Mahoney et al. (2014b) demonstrated using a simple detection task that older adults' responses to visuotactile multisensory stimuli were significantly faster than responses to the constituent unisensory stimuli, regardless of whether visual and tactile stimuli were presented on the same or different side. It should be noted that there have been studies targeting young adults that did not find the effect of spatial consistency of visuotactile stimuli when a simple detection task was used (e.g., Forster et al. 2002; Girard et al. 2011). Recently, Couth et al. (2016) provided further evidence that older adults exhibited visuotactile interactions in a broader spatial range than younger adults using a modified unimanual version of crossmodal congruency task (Poole et al. 2015). In Couth et al. (2016), visual distractors were presented at a distance of 0, 21, or 42 vertically from the stimulated hand or 42 cm horizontally from the stimulated hand in the opposite hemispace (i.e., in proximity to the unstimulated hand). Older adults exhibited visuotactile congruency effects, irrespective of whether the visual distractors were presented close to the simulated hand or close to the 42 cm horizontally separated unstimulated hand. This is consistent with previous studies (Mahoney et al. 2014b; Poliakoff et al. 2006a). Notably, the visuotactile congruency effect was observed when the visual distractor was separated vertically by 21 cm but not by 42 cm. These results differ from those of younger adults (Poole et al. 2015), in which the visuotactile congruency effect only occurred in proximity to the stimulated hand. These findings indicate that the spatial relationship between visual and tactile stimuli is still relevant to older adults' visuotactile interactions and that the spatial range within which the visuotactile interaction occurs could change with age.

The spatial extent to which visuotactile interactions strongly occur is known as visuotactile peripersonal space (hereafter called "peripersonal space") (e.g., Previc 1998; Rizzolatti et al. 1981). Single-cell recordings in monkeys have demonstrated that there are neurons that respond not only to tactile stimuli on the body surface but also to visual stimuli presented close to the body. The firing rate of these neurons is reported to be inversely proportional to the distance of visual stimuli from the body surface (Bremmer et al. 2001; Duhamel et al. 1998; Graziano and Gross 1993; Graziano et al. 1994, 1997; Rizzolatti et al. 1981, 1983, 1997, 1998). In humans, evidence for peripersonal space has been provided by patients with right brain damage (RBD) exhibiting extinction (di Pellegrino et al. 1997; Làdavas et al. 1998a, b; Làdavas and Farnè 2004a, b) and healthy human adults (e.g., Sambo and Forster 2009; Teramoto and Kakuya 2015). Similar to studies with monkeys, the distance between a visual target and body surface is reported to be crucial for humans; visuotactile interactions decrease with an increase in the distance of visual stimuli from a bodily surface. Considering these previous findings regarding peripersonal space, the results of Couth et al. (2016) suggest that peripersonal space might expand in a certain direction for older adults as compared to younger adults. However, studies focusing on older adults' performance only tested conditions where the visual and tactile stimuli were separated horizontally and vertically. It remains unclear how peripersonal space expands in a sagittal direction in older adults. Thus, the present study investigated how age difference affected peripersonal space in a sagittal direction, using a redundant target paradigm.

The present study additionally explored the association between declines in sensorimotor functions related to gait and balance, and visuotactile interaction. Setti et al. (2011) investigated differences in audiovisual crossmodal interactions between older adults with and without a history of falls using a double flash illusion (Shams et al. 2000). Results revealed that older adults with a history of falls were more susceptible to the double flash illusion and had a wider temporal window for integration between auditory and visual information compared to age-matched older adults without a history of falls. In a subsequent study, Stapleton et al. (2014) investigated the direct association between audiovisual crossmodal interaction and balance control in older adults with a history of falls. They found that the fall-prone older adults were more susceptible to this illusion in a standing as compared to a sitting position. Furthermore, Merriman et al. (2015) demonstrated that a balance training intervention using a virtual reality display decreased the susceptibility to the double flash illusion in fall-prone older adults. For visuotactile interactions, Mahoney et al. (2014a), using a redundant target paradigm, demonstrated that older adults who showed reaction time (RT) facilitation from visuotactile crossmodal stimuli (75% of their participants) had less postural stability and an increased history of falls than did those who did not show multisensory facilitation. Taken together, these findings suggest a close link between multisensory interactions and sensorimotor functions related to gait and balance among older adults (see also Mahoney et al. 2015). Considering that balance maintenance is achieved via information from several sensory modalities such as vision, touch, proprioception, and the vestibular system (Horak and Macpherson 1996), older adults with difficulties in gait and balance control might have a problem with general multisensory processing (Setti et al. 2011). Thus, the present study aimed to clarify the relationship between the spatial extent of peripersonal space and older adults' abilities to control gait and posture.

## Materials and methods

### Participants

Twenty-five community-dwelling older adult men (mean age: 75.0 ± 3.3 years) were recruited via a local branch of national human resource center for seniors. Of these older adults, five were excluded: two were not able to complete the tasks, and the others scored lower than 24 on the Mini Mental State Examination (MMSE, Folstein et al. 1975; Foreman et al. 1996), indicating mild cognitive impairment. The age range for the remaining 20 older adults was 71–82 years (mean age 74.6 ± 2.9 years). The participants did not have any type of dementia, depression, stroke, Parkinsonism, visual impairment, or current treatment with neuroleptics. Eleven undergraduate male students (aged 20–22 years, mean age 21.4 ± 0.70 years) with normal or corrected-to-normal visual acuity also took part in this experiment. All the older and young participants were right-handed. This study followed the tenets of the Declaration of Helsinki, and the Ethics Committee of Kumamoto University approved the protocol. The participants provided informed written consent to participate in this study before commencement of the experimental sessions.

### Apparatus and stimuli

The participants were seated in a dimly lit experimental chamber, resting their hands on a table in front of them. They placed their left and right index fingers on vibrotactile stimulators (M-PZT-02, Eishin Denki CO. LTD, Japan) set 22 cm to the left and right of their midline, respectively, at a distance of approximately 50 cm from their body. The vibration amplitude was set far above the detection threshold at a frequency of 300 Hz. Two sets of three white light emitting diodes (LEDs) 3 mm in diameter were placed 22 cm to the left and right of their midline, respectively (Fig. 1). The LEDs were placed at 5 cm (near), 37.5 cm (middle), and 70 cm (far) from the vibrotactile stimulator on each side. A red fixation cross was placed at the center of the table, midway between the left and right LEDs. Stimulus duration was 100 ms. Synchronization of the visual and tactile stimulus onset was confirmed using a digital oscilloscope. The experiment was

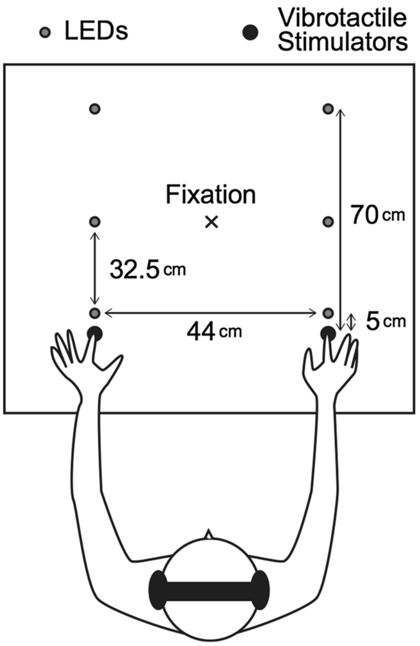

**Fig. 1** Schematic illustration of the experimental setup (*top view*). Participants placed their left and right index fingers on the left and right vibrotactile stimulators, respectively. Visual stimuli were presented on six possible locations at the near, middle, and far space within the two hemispaces. To mask any noise created while operating the vibrotactile stimulators, a white noise was presented continuously via headphones, at 68 dB SPL, throughout the experiment

controlled by a Mac-mini (OSX 10.7) with MATLAB and Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997; Kleiner et al. 2007). The digital signals from the LEDs and vibrotactile stimulators were converted to analog signals using audio interfaces (Octa-capture, U-1010, Roland, Japan). To mask any noise generated while operating the vibrotactile stimulators, a white noise was presented via headphones, at 68 dB SPL (sound pressure level) continuously throughout the experiment.

### Assessments of cognitive, sensory, and sensorimotor function in the older adults

Visual acuity was measured at 40 cm and 3 m using Landolt C charts. The somatosensory sensitivity of the left and right index fingers was measured using the Von Frey Touch Test (von Frey 1896; Semmes–Weinstein Monofilaments, North Coast Medical Inc., USA). This test can measure the minimum force required for participants to feel touch on the skin. Each participant's level of general cognitive functions was quantified with the MMSE (Folstein et al. 1975; Foreman et al. 1996). As mentioned previously, participants whose MMSE score was lower than 24 were excluded from the sample, due to suspected cognitive impairment. Participants' executive functions, including attentional control and task switching, were assessed with the Trail Making Test (TMT) (Arbuthnott and Frank 2000a, b; Gaudino et al. 1995; Miner and Ferraro 1998). The TMT consists of two parts (A and B). In TMT-A, the participants were asked to draw lines sequentially, to connect 25 consecutive numbers (i.e., 1–2–3–…) that were randomly distributed on a sheet. In TMT-B, the participants were asked to draw lines to alternately connect numbers (1–13) and letters (A–L) in an ascending order (i.e., 1–A–2–B–3–…), also randomly distributed on a sheet. The TMT-A and TMT-B were administered in this order. In both these tests, the participants were asked to perform the task as accurately and as quickly as possible. The time taken to complete the task was measured. Response time differences between A and B (B minus A) were calculated to provide an index of executive functions.

To assess participants' sensorimotor functions related to gait and balance, the Timed Up and Go (TUG) (Podsiadlo and Richardson 1991; Shumway-Cook et al. 2000) and postural stability tests were used. These tests are the most common clinical tools for examining functional mobility and fall risk in older adults (Piirtola and Era 2006; Shumway-Cook et al. 2000). During the TUG test, the participants were asked to stand up from a standard chair with a seat height of 40 cm, walk at a comfortable speed to a marker placed at a distance of 3 m, turn, walk back to the chair, and sit down. The time was measured from the point when the participants arose from the chair to when they were re-seated with a stop-watch. Each participant performed this test twice. The average time spent on the two trials was used as the TUG score. During the postural stability test, the participants were asked to stand at the center of a force plate (Wii Balance Board; Nintendo, Kyoto, Japan) placed 2 m away from a white wall. There were two trials each, for eyes-open and eyes-closed conditions. In the eyes-open trials, the participants were asked to keep looking at a fixation on the wall. Sampling was performed at 100 Hz, for 60 s. Average movement path length of the center-of-pressure (COP), which is the location of the global ground reaction force at the surface of support (Newell and Slifkin 1998), for each condition was used as a measure of postural stability.

## Procedure

Twelve older participants underwent the cognitive, sensory, and sensorimotor assessments first and the psychophysical experiment next. The remaining 13 older participants underwent the tasks in reverse order. The procedure of the psychophysical experiment was also used for our previous study, which successfully revealed the range of young participants' peripersonal space in the sagittal direction (Teramoto and Kakuya 2015). The participants were required to produce speeded responses to all stimuli appearing in one hemispace (left or right), irrespective of spatial distance (near/middle/far) and target modality (visual/tactile/visuotactile). Before the experimental session, an experimenter informed the participants as to the side they should respond. For several trials, tactile stimuli appeared on the opposite side, but participants were instructed to refrain from responding to those trials (catch trials). Responses were recorded when the participants depressed a foot-pedal placed under the preferred foot (all participants except for two young participants depressed it with their right foot). Each participant completed two experimental sessions where target stimuli were presented in the left and right hemispace to investigate the whole far space in the sagittal direction. The order of the sessions was counterbalanced across participants. Each session consisted of 80 trials: 10 for each of the tactile only (T), visual only (V:$V_{near}$, $V_{middle}$, and $V_{far}$), and visuotactile (VT:$VT_{near}$, $VT_{middle}$, and $VT_{far}$) conditions and 10 for the catch trials. The order of the conditions was randomized. The inter-trial interval was randomly chosen from 1000 to 1500 ms. Before the experimental sessions, each participant completed one practice session of 20 trials to ensure that the tasks were understood. The participants were instructed to keep looking at the fixation point throughout the experimental session and not look directly at their hands (but the gaze behavior was not monitored during the experimental session). Thus, the participants were able to see all LEDs clearly, while their hands were faintly visible.

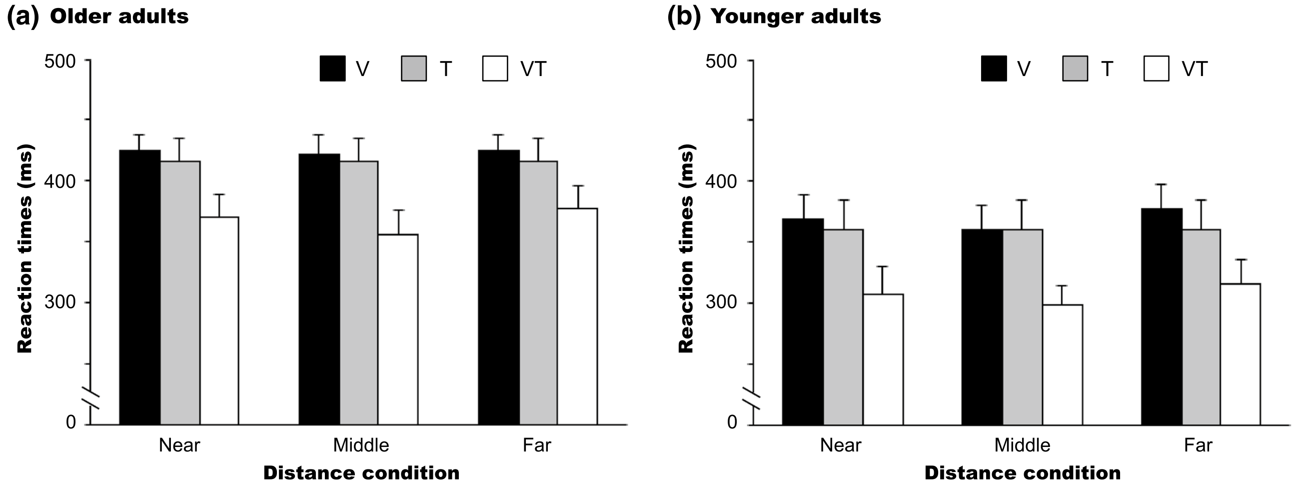

**Fig. 2** Average reaction times across participants in each age group for the visual stimulus only (V), tactile stimulus only (T), and visuotactile (VT) trials in the near and far conditions. Note that the average RTs for the tactile only condition (*gray bars*) in each distance condition were identical. The *error bars* represent the within-participants standard error of the mean

## Results

Trials in which the RTs exceeded ±3 SD were discarded from the following analyses as errors. Error rates, including no response errors, were 3.5 ± 2.8% for the older adults and 3.0 ± 4.1% for the younger adults. False alarm rates for catch trials were 9.5 ± 9.0 and 10.0 ± 10.5% for the older and younger adults, respectively. No significant differences between groups were observed, for either the error rates ($t_{29} = 0.38$, $p = .704$, $d = 0.14$) or for the false alarm rates ($t_{29} = 0.14$, $p = .886$, $d = 0.05$). Median RTs were calculated for each participant in each condition and averaged across participants in each group (Fig. 2). Note that the average RTs for the tactile only condition (gray bars) were identical across the distance conditions. The data analysis were performed after combining the two experimental sessions where target stimuli were presented in the left and right hemispace.[1]

The first analysis examined whether the detection performance for unisensory target trials (T-only or V-only condition) differed between the age groups. For the T-only trials, a *t* test revealed no significant difference between the age groups ($t_{29} = 1.85$, $p = .074$, $d = 0.69$). For the V-only condition, a two-way mixed analysis of variance (ANOVA) was performed with group as a between-subjects factor and distance as a within-subjects factor. There was a significant effect of group ($F_{1,29} = 6.35$, $p = .018$, $\eta^2_G = 0.153$): the RTs in the V-only condition were shorter for the younger than older adults. However, no effect of distance or the interaction effect was observed (distance: $F_{2,58} = 0.65$, $p = .526$, $\eta^2_G = 0.004$; group × visual distance: $F_{2,8} = 0.39$, $p = .679$, $\eta^2_G = 0.002$). Thus, the distance of visual target did not affect detection performance of visual stimuli themselves for either age group.

The second analysis examined the redundant target effects (RTEs), that is, whether a decrease in RTs appeared when stimuli were simultaneously presented to two sensory modalities as compared to when stimuli were presented to a single sensory modality. A two-way mixed-design ANOVA was performed on the RT data of each distance with group as a between-subjects factor and target modality as a within-subjects factor. A main effect of target modality was significant for all distance conditions (near: $F_{2,58} = 15.34$, $p < .001$, $\eta^2_G = 0.102$; middle: $F_{2,58} = 22.82$, $p < .001$, $\eta^2_G = 0.130$; far: $F_{2,58} = 12.56$, $p < .001$, $\eta^2_G = 0.863$). Multiple comparison tests (Bonferroni correction, $\alpha < 0.05$) revealed that the RTs for the VT condition were shorter than those for either of the target modalities alone and there was no difference between the unisensory conditions. An effect of group was also significant for all distance conditions: the younger adults exhibited shorter RTs than older ones (near: $F_{1,29} = 5.53$, $p = .026$, $\eta^2_G = 0.130$; middle: $F_{1,29} = 5.36$, $p = .028$, $\eta^2_G = 0.130$; far: $F_{1,29} = 4.94$, $p = .034$, $\eta^2_G = 0.118$), but no interaction was observed ($F_{2,58} < 0.22$, $p > .803$,

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[1] Although the laterality of the effects was beyond the scope of the present study and the number of trials on each side in each condition was very small (only ten per participant), we tried to investigate laterality with the current data for supplemental information. The results of this analysis revealed that redundant target effects occurred especially on the left side, near condition in the young/old comparison data, and near and middle conditions for the TUG and postural sway classification data. Considering all participants were right-handed, handedness might affect the RTEs somehow. Unfortunately, we did not perform the race model analysis because the number of RT data per condition was too small.

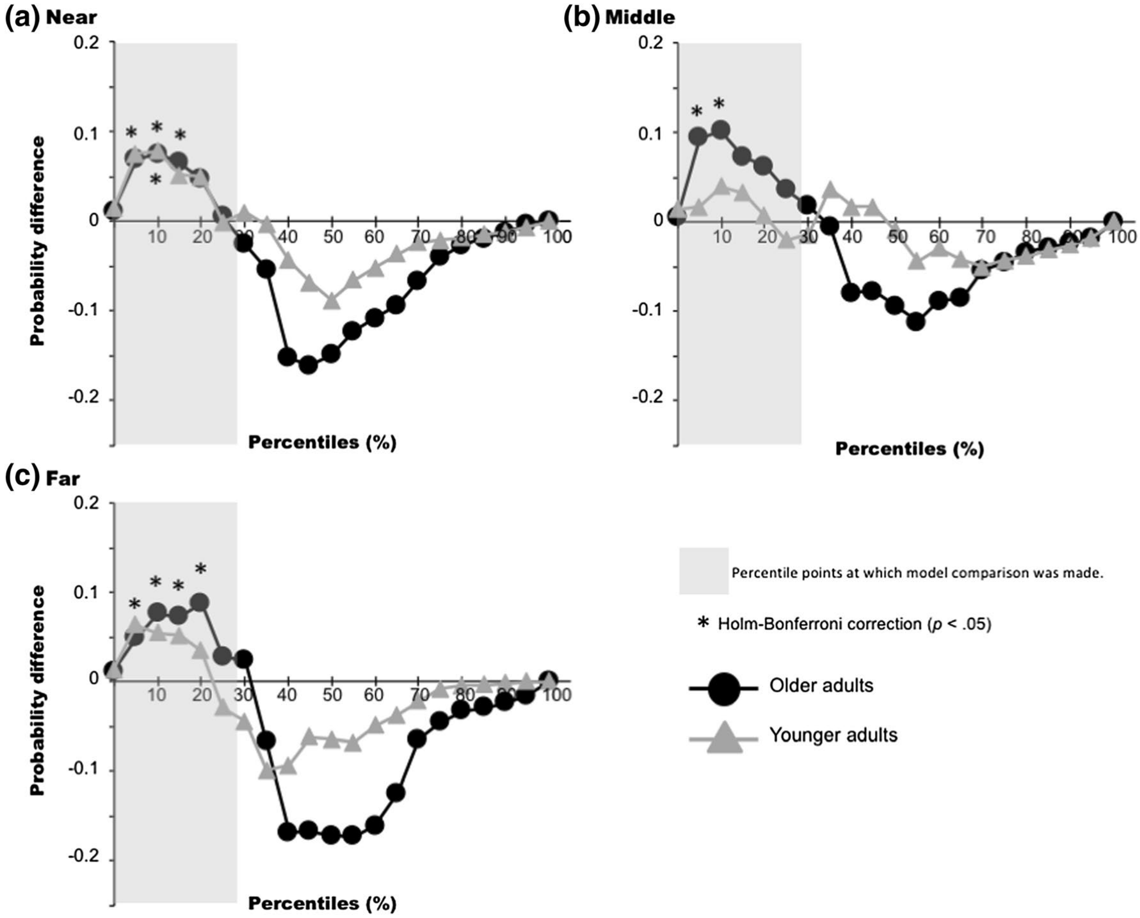

**Fig. 3** Results of Miller's race model test. Cumulative probability difference curves between visuotactile stimuli (VT) and the sum of unisensory stimuli (V + T) are shown as functions of reaction time percentiles; near (**a**), middle (**b**), and far (**c**) conditions. These values were calculated by subtracting the cumulative probability functions (CDFs) predicted by the probability summation of the race model (i.e., V + T) from the CDFs of the VT condition. Values greater than zero indicate violation of the race model. *Asterisks* indicate significant differences between the V + T (predicted VT) and (actual) VT conditions (Holm-Bonferroni correction, $p < .05$)

$\eta_G^2 < 0.002$). These results indicate that the detection was faster when two sensory modalities were stimulated at the same time than when these modalities were independently stimulated (i.e., RTEs) for all age groups and distance conditions.

The next analysis tested whether the multisensory facilitation effect could be accounted for by the statistical facilitation, which was predicted by probability summation using Miller's race model of inequality (Miller 1982). To do this, the algorithm described in Ulrich et al. (2007) was used and applied for each of the near, middle, and far conditions for each participant. The details are as follows. First, the RT range was calculated across all conditions and quantized into 20 bins from the fastest RT (zero percentile) to the slowest RT (hundred percentile) with a bin width of 5%. Then, two cumulative probability density functions (CDFs) were estimated for the VT and for the sum of the V and T (V + T) conditions, respectively. Subsequently, the average CDFs across participants were calculated. Finally, for the first five percentiles after 0 (from 5th to 25th), the VT and V + T were compared using a two-tailed $t$ test with Bonferroni-Holm corrections (Holm 1979; significance level: $p < .05$). The percentile range of comparisons followed the analysis used in Mahoney et al. (2014a) and recommended by Kiesel et al. (2007) to avoid accumulating Type I errors. The differences between the grouped CDFs for the VT and V + T conditions at each distance condition are shown in Fig. 3. If significantly faster RT in the VT than V + T (predicted VT) conditions is observed at any

**Table 1** Characteristics of the older participants in $\text{HIGH}_{\text{TUG}}$ and $\text{LOW}_{\text{TUG}}$ groups

| | High ($N = 10$) | Low ($N = 10$) | $t$ value | $p$ value | Cohen's $d$ |
|---|---|---|---|---|---|
| Age | 73.9 | 75.2 | 1.01 | 0.33 | 0.45 |
| MMSE | 26.2 | 26.5 | 0.34 | 0.74 | 0.15 |
| Tactile test | 2.76 | 2.74 | 0.06 | 0.95 | 0.028 |
| Visual acuity (3 m) | 0.79 | 0.6 | 1.34 | 0.21 | 0.598 |
| Visual acuity (40 cm) | 0.37 | 0.33 | 0.45 | 0.66 | 0.201 |
| TMT (B–A) | 20.81 | 29.24 | 0.63 | 0.53 | 0.283 |
| TUG | 7.52 | 9.47 | 5.55 | 0 | 2.475 |
| Balance (eyes closed) (cm) | 190.04 | 189.25 | 0.05 | 0.96 | 0.022 |
| Balance (eyes open) (cm) | 171.51 | 162.42 | 0.69 | 0.5 | 0.31 |

percentile in a condition (shown as asterisks in Fig. 3), it can be concluded that the race model is violated (i.e., some form of genuine visuotactile interaction occurs) in that condition (Ulrich et al. 2007).[2] In the near condition, significant violation of the race model prediction was observed for both age groups: from the 5th to 15th percentiles for the older adult group and the 10th percentile for the younger adult group. In the middle and far conditions, significant violation of the race model prediction was observed only for the older adult group (5th and 10th percentiles in the middle condition and from 5th to 20th percentiles in the far condition). These results suggest that visuotactile multisensory integrative process occurs over a large area in the sagittal direction for the older adult group, while it occurs in a limited spatial range from the body surface for the young adult group.

## Classification by TUG scores

To investigate whether the peripersonal space for older adults was linked to the decline in sensorimotor functions, older adults were divided into two groups based on their TUG scores (lower scores indicate better performance). After the TUG scores were listed in ascending order, the top 10 older adults were assigned to the high sensorimotor performance group ($\text{HIGH}_{\text{TUG}}$), and the remaining 10 were assigned to the low sensorimotor group ($\text{LOW}_{\text{TUG}}$). The average TUG scores for the former and latter groups were 7.52 s (SD = 0.70) and 9.47 s (SD = 0.87), respectively. The average scores on each assessment for each group have been listed in Table 1. Unpaired $t$ tests (two-tailed) revealed no significant differences between groups across all assessments ($ts_{18} < 1.34$, $ps > .205$), except in the TUG scores ($t_{18} = 5.55$, $p < .001$). Error rates, including no response errors, were 1.3 ± 1.6% for the $\text{HIGH}_{\text{TUG}}$ group and 3.2 ± 3.5% for the $\text{LOW}_{\text{TUG}}$ group. False alarm rates for catch trials were 9.5 ± 8.3% for the $\text{HIGH}_{\text{TUG}}$ group and 9.5 ± 9.0% for the $\text{LOW}_{\text{TUG}}$ group. No significant differences between groups were observed, for either the error rates ($t_{18} = 1.54$, $p = .141$, $d = 0.69$) or for the false alarm rates ($t_{18} = 0.00$, $p = 1.0$, $d = 0.0$). Figure 4 shows the average RT across participants in each condition in each group.

Group differences in unisensory target detection were examined. A $t$ test revealed that the detection of tactile unisensory targets did not differ between the $\text{HIGH}_{\text{TUG}}$ and $\text{LOW}_{\text{TUG}}$ groups ($t_{18} = 0.19$, $p = .852$, $d = 0.08$). As for the detection performance of visual unisensory targets, a two-way mixed ANOVA showed no significant main or interaction effect (group: $F_{1,18} = 0.09$, $p = .774$, $\eta^2_G = 0.003$; distance: $F_{2,36} = 0.03$, $p = .971$, $\eta^2_G < 0.001$; group × distance: $F_{2,36} = 2.30$, $p = .115$, $\eta^2_G = 0.025$). Thus, tactile and visual target detection did not significantly differ between the groups or across distance conditions. Next, a two-way mixed ANOVA was performed on the data of each distance condition with group as a between-subjects factor and target modality as within-subjects factor to investigate whether the RTEs occurred. There was a significant effect of target modality for all distance condition (near: $F_{2,36} = 9.68$, $p < .001$, $\eta^2_G = 0.099$; middle: $F_{2,36} = 23.55$, $p < .001$, $\eta^2_G = 0.134$; far: $F_{2,36} = 7.44$, $p = .002$, $\eta^2_G = 0.072$), and no other effect except for the interaction for the middle distance condition ($F_{2,36} = 4.50$, $p = .028$, $\eta^2_G = 0.029$) was observed. For the near and far conditions, multiple comparison tests (Bonferroni correction, $\alpha < 0.05$) revealed that the RTs for the VT condition were shorter than those for either of the target modalities alone and there was no difference between the unisensory conditions. For the middle condition, a simple effect of target modality was observed for both participant groups ($\text{HIGH}_{\text{TUG}}$: $F_{2,36} = 5.26$, $p = .010$; $\text{LOW}_{\text{TUG}}$: $F_{2,36} = 22.78$, $p < .001$) and the results of multiple comparison tests were the same as those for the other distance conditions ($\alpha < 0.05$). These

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[2] Some recent studies have used a slightly different criterion for the violation of race model (e.g., Colonius and Diederich 2006; Mahoney et al. 2011, 2014a). However, the present study adopts the conventional procedure (e.g., Gondan and Minakata 2016; Miller 1982).

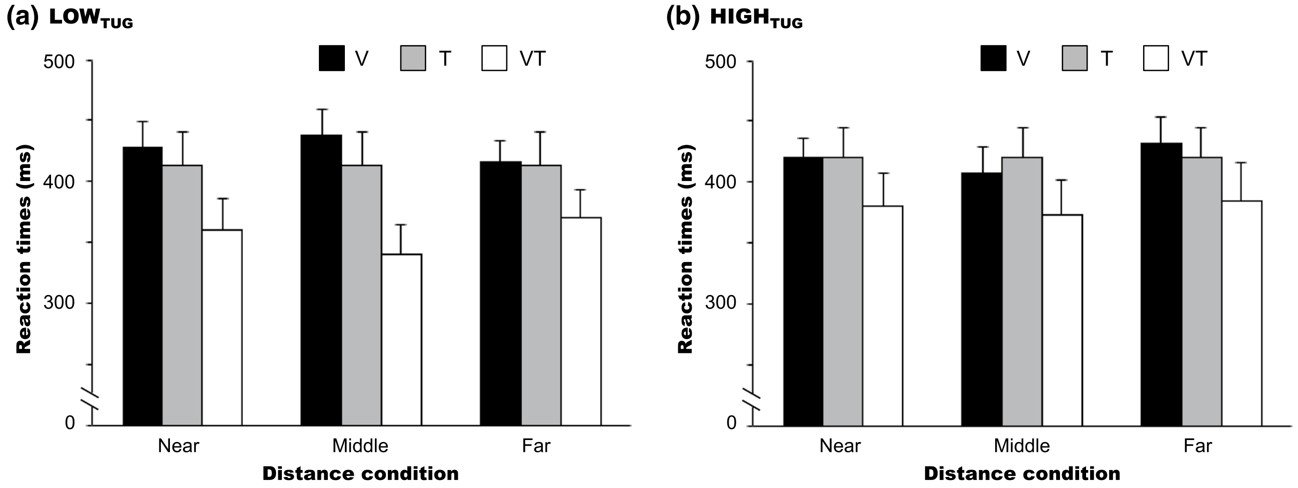

**Fig. 4** Average reaction times across participants in each group of older adults for the visual stimulus only (V), tactile stimulus only (T), and visuotactile (VT) trials in the near and far conditions. Older adults were classified based on the TUG scores. Decreased and better TUG performance groups are represented as LOW$_{TUG}$ and HIGH$_{TUG}$, respectively. The *error bars* represent the within-participants standard error of the mean

results indicate that visuotactile redundant targets facilitated detection performance, irrespective of group and visual target distance.

The race model inequality test was also performed as described above. The differences between grouped CDFs for the VT and V + T conditions for each distance condition are presented in Fig. 5 (the data for young adults were the same as those shown in Fig. 3). In all distance conditions, significant violation of the race model prediction was observed for the LOW$_{TUG}$ groups but not for the HIGH$_{TUG}$ group (near: 5th percentile; middle: all targeted percentiles; far: from 5th to 20th percentiles). These results suggest that visuotactile multisensory integrative process is different between the LOW$_{TUG}$ and HIGH$_{TUG}$ groups and the peripersonal space for the former group encompasses a broad rage in the sagittal direction.

## Classification based on the postural stability test

The same analyses described in the previous section were performed for data grouped based on the postural stability test scores. Since nearly the same data were obtained for the eyes-open and eyes-closed conditions, only the results classified by the eyes-closed condition have been reported in this paper. The top 10 older participants whose posture was most stable were assigned to a high sensorimotor performance group (HIGH$_{pos}$), and the remaining 10 were assigned to a low sensorimotor group (LOW$_{pos}$). Among the participants assigned in the LOW$_{pos}$ group, six participants were included in the low TUG sensorimotor group as well (i.e., LOW$_{TUG}$ group). The average COP path length for the former and latter groups was 164.97 cm (SD = 16.65) and 214.32 cm (SD = 31.77), respectively. The average scores on each assessment in each group have been listed in Table 2. Unpaired *t* tests (two-tailed) revealed no significant differences between groups across all assessments ($ts_{18} < 1.34$, $ps > .20$), except for the postural stability tests (eyes-closed: $t_{18} = 4.08$, $p = .001$, eyes-open: $t_{18} = 3.34$, $p = .004$).

Error rates, including no response errors, were 2.8 ± 4.1% for the HIGH$_{pos}$ group and 3.3 ± 4.5% for the LOW$_{pos}$ group. False alarm rates for the catch trial were 9.5 ± 10.1% for the HIGH$_{pos}$ group and 9.5 ± 6.9% for the LOW$_{pos}$ group. No significant differences between groups was observed, for either the error ($t_{18} = 0.28$, $p = .785$, $d = 0.12$) or the false alarm rates ($t_{18} = 0.00$, $p = 1.00$, $d = 0.0$). Figure 6 shows the average RTs for each condition in each group. Data for the young group was the same as that presented in Fig. 2. Note that average RTs for the tactile only condition (gray bars) were identical across the distance conditions.

To examine whether detection with a single modality varied across group and/or distance, a *t* test on the T-only data and a two-way mixed ANOVA with group as a between-subjects factor and distance as a within-subjects factor were performed. The *t* test for the T-only condition revealed no effect of group ($t_{18} = 0.58$, $p = .569$, $d = 0.26$). The two-way ANOVA revealed no effect of group ($F_{1,18} = 0.81$, $p = .381$, $\eta^2_G = 0.034$) or distance ($F_{2,36} = 0.03$, $p = .972$, $\eta^2_G < 0.001$) and no interaction was present between group and distance ($F_{2,36} = 1.67$, $p = .204$, $\eta^2_G = 0.019$). Thus, tactile and visual target detection was not significantly different between groups and across visual distance. Next, a two-way mixed ANOVA was performed in the same design as used in

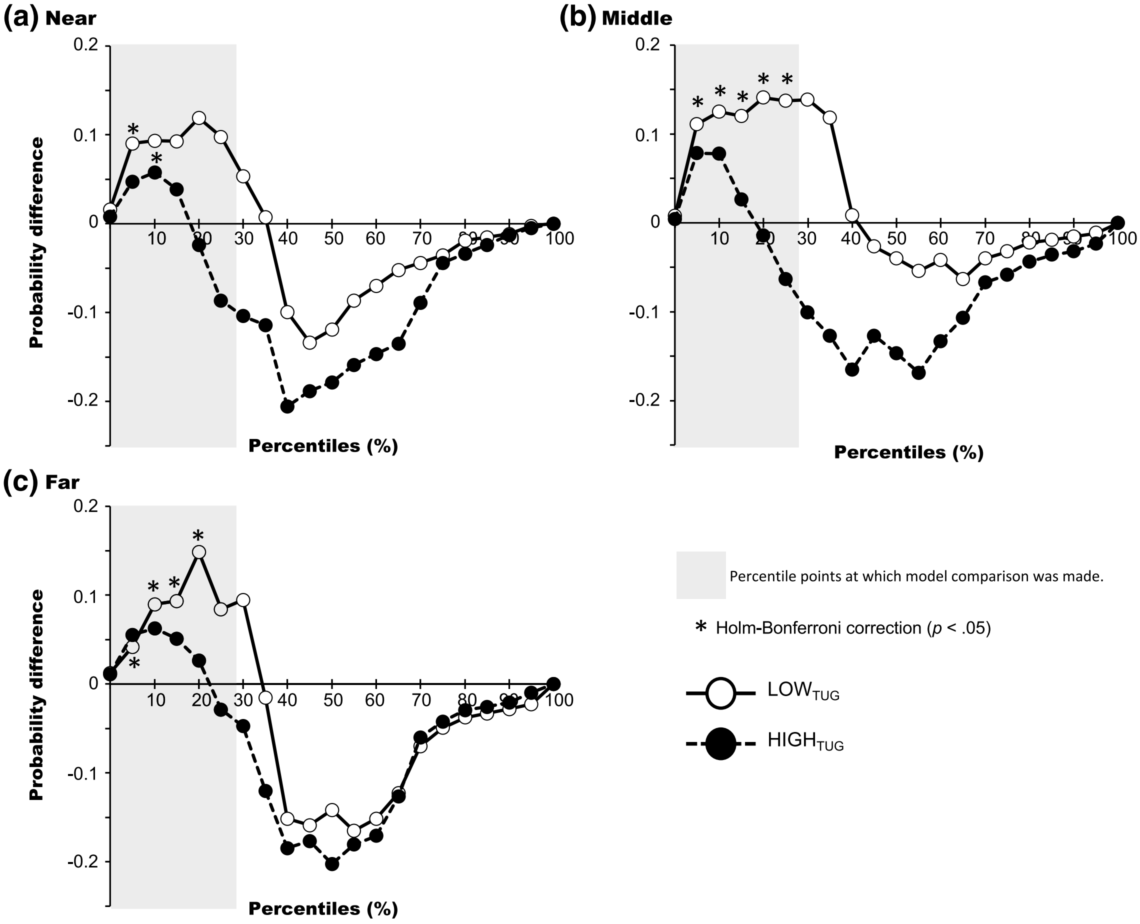

**Fig. 5** Results of Miller's race model test for older adults with low and high TUG scores (LOW$_{TUG}$ and HIGH$_{TUG}$, respectively). Cumulative probability difference curves between visuotactile stimuli (VT) and the sum of unisensory stimuli (V + T) are shown as a function of reaction time percentiles; near (**a**), middle (**b**), and far (**c**) conditions. These values were calculated by subtracting the cumulative probability functions (CDFs) predicted by the probability summation of the race model (i.e., V + T) from the CDFs of the VT condition. Values greater than zero indicate violation of the race model. *Asterisks* indicate significant differences between the V + T (predicted VT) and (actual) VT conditions (Holm-Bonferroni correction, $p < .05$). Results for younger adults are identical to those shown in Fig. 3

**Table 2** Characteristics of the older participants in HIGH$_{pos}$ and LOW$_{pos}$ groups

| | High ($N = 10$) | Low ($N = 10$) | *t* value | *p* value | Cohen's *d* |
|---|---|---|---|---|---|
| Age | 73.7 | 75.4 | 1.34 | 0.2 | 0.6 |
| MMSE | 26.6 | 26.1 | 0.56 | 0.58 | 0.251 |
| Tactile test | 2.74 | 2.76 | 0.06 | 0.95 | 0.027 |
| Visual acuity (3 m) | 0.76 | 0.64 | 0.82 | 0.43 | 0.367 |
| Visual acuity (40 cm) | 0.32 | 0.37 | 0.5 | 0.62 | 0.225 |
| TMT (B–A) (s) | 24.99 | 25.06 | 0.01 | 1 | 0.002 |
| TUG (s) | 8.24 | 8.75 | 0.91 | 0.38 | 0.406 |
| Balance (eyes closed) (cm) | 164.97 | 214.32 | 4.08 | 0 | 1.946 |
| Balance (eyes open) (cm) | 149.03 | 184.9 | 3.34 | 0 | 1.57 |

the TUG classification to investigate whether the RTEs occurred. There was a significant effect of target modality for all distance condition (near: $F_{2,36} = 9.69$, $p < .001$, $\eta^2_G = 0.100$; middle: $F_{2,36} = 19.21$, $p < .001$, $\eta^2_G = 0.136$; far: $F_{2,36} = 7.44$, $p = .002$, $\eta^2_G = 0.073$), and no other effect was observed. Multiple comparison tests (Bonferroni correction, $\alpha < .05$) revealed that the RTs for the VT condition were shorter than those for either of the target

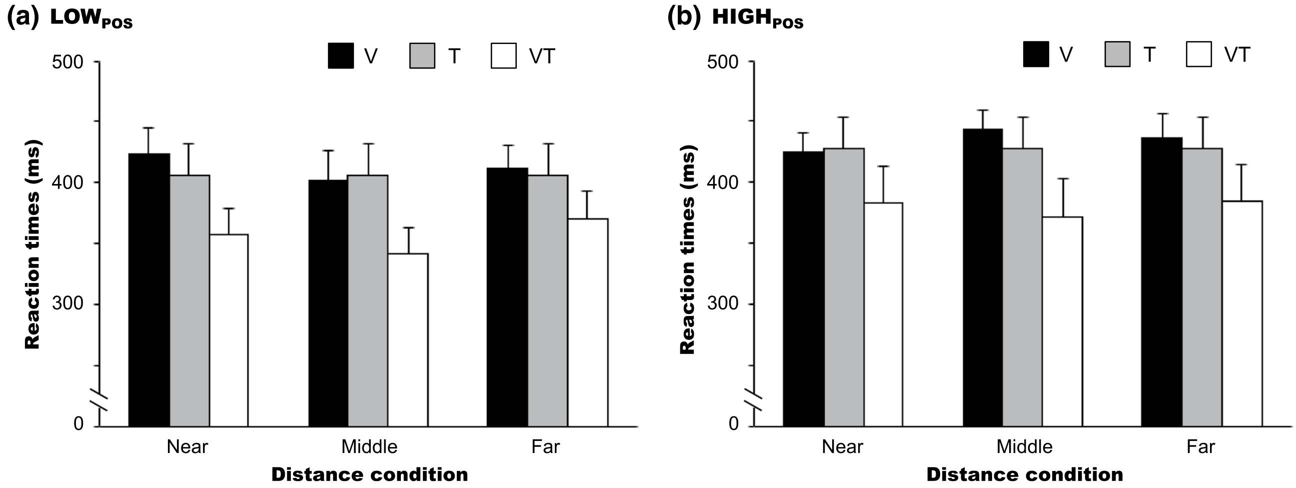

**Fig. 6** Average reaction times across participants in each group of older adults for the visual stimulus only (V), tactile stimulus only (T), and visuotactile (VT) trials in the near and far conditions. Older adults were classified based on postural stability test scores (the closed-eye condition). Low and high postural stability performance groups are represented as LOW$_{pos}$ and HIGH$_{pos}$, respectively. *Error bars* represent within-participant standard errors of the mean

modalities alone and there was no difference between the unisensory conditions. These results indicate that visuotactile redundant targets facilitated detection performance, irrespective of group and visual target distance.

The race model inequality test was also performed as described above. The differences between grouped CDFs for the VT and V + T conditions for each distance condition are presented in Fig. 7 (the data for young adults were the same as those shown in Fig. 3). While no significant violation of race model prediction was observed in any distance condition for the HIGH$_{pos}$ group, significant violations were observed in all distance conditions for the LOW$_{pos}$ group except for the middle condition (from the 5th and 15th percentiles in the near conditions and at the 5th percentile in the far condition). Thus, the older participants in the LOW$_{pos}$ group exhibited visuotactile interactions over a large area in the sagittal direction.

## Discussion

The present study investigated the effect of age on the spatial extent of visuotactile interactions, and its link to sensorimotor gait and balance ability in older adults. Visuotactile interactions were investigated with a redundant target paradigm and a race model analysis. Sensorimotor functions related to gait and balance were assessed using the TUG and postural stability tests. Results showed that RTEs were observed for all participant groups and distances, while performance on constituent unisensory visual and/or tactile stimulus detection was not different across the groups and distances. Notably, the race model analysis revealed that visuotactile interactions emerged even in far space in the sagittal direction for older adults, whereas it was limited to the near space for younger adults. The detailed analysis using the TUG and postural stability test scores in the older adults further demonstrated that the enhanced visuotactile interactions were especially prevalent among the older adults with relatively poor TUG and postural stability performance. These findings suggest a potential link between visuotactile interaction and decreased gait and balance functions in older adults.

Several studies have shown enhanced multisensory interactions with aging (e.g., Couth et al. 2016; DeLoss et al. 2013; Diederich et al. 2008; Laurienti et al. 2006; Mahoney et al. 2011, 2014b; McGovern et al. 2014; Peiffer et al. 2007; Poliakoff et al. 2006a). The results suggests that, for older adults, the space where visuotactile interactions occur is likely to be extended not only in the horizontal (lateral) and vertical directions (Couth et al. 2016; Mahoney et al. 2014b; Poliakoff et al. 2006a), but also in the sagittal direction. Previous studies also reported a close link between older adults' sensorimotor functions related to gait and balance, and enhanced multisensory interactions (Mahoney et al. 2014a; Merriman et al. 2015; Setti et al. 2011; Stapleton et al. 2014). The present study provides further evidence in the literature on this topic.

It should be noted that there are several potential confounds and limitations relevant to experiments described in this study. First, one would argue that the differences in the visual target distance from the fixation point and the stimulus location and size defined by visual angle had some effects on visuotactile interactions, and several previous

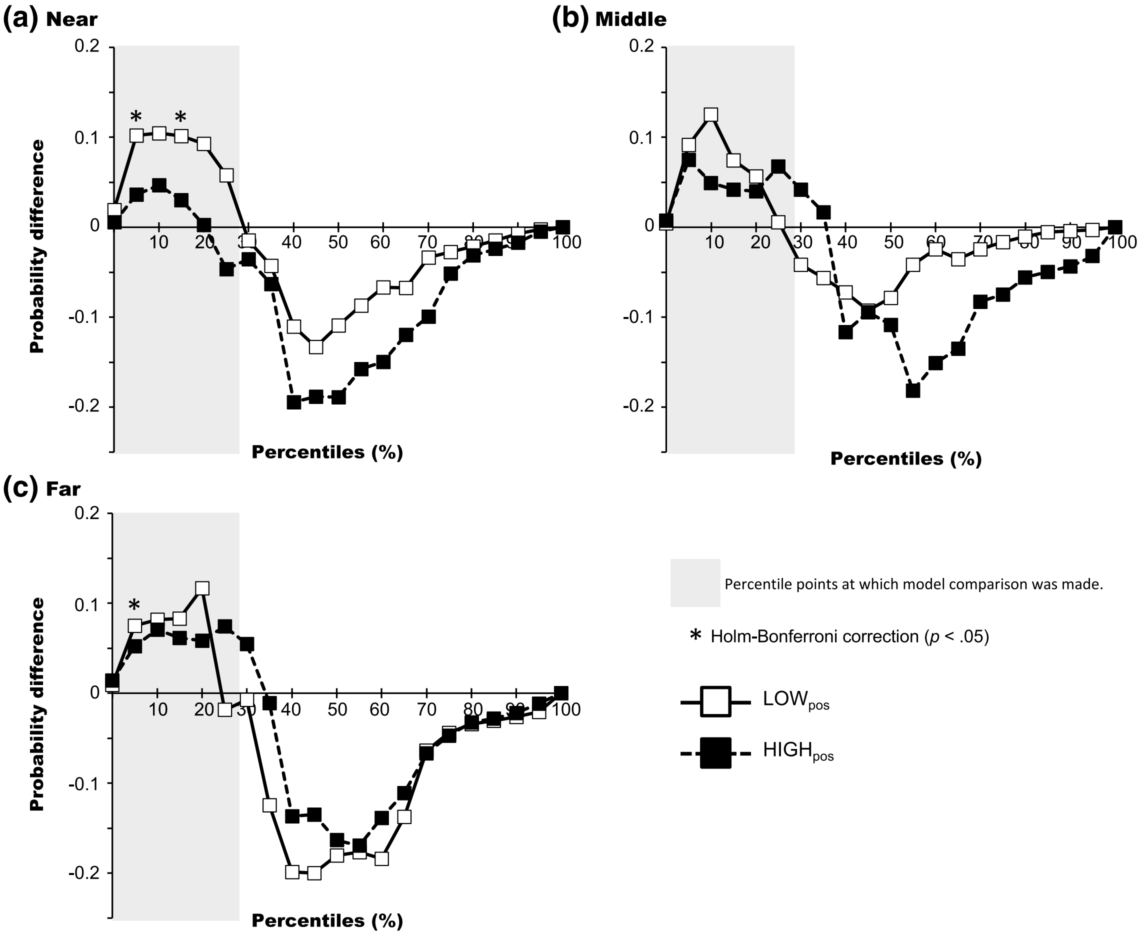

**Fig. 7** Results of Miller's race model test for older adults with low and high postural stability test scores (LOW$_{pos}$ and HIGH$_{pos}$, respectively). The cumulative probability difference curves between the visuotactile stimuli (VT) and the sum of unisensory stimuli (V + T) are shown as a function of the reaction time percentiles; near (**a**), middle (**b**), and far (**c**) conditions. These values were calculated by subtracting the cumulative probability functions (CDFs) predicted by the probability summation of the race model (i.e., V + T) from the CDFs of the VT condition. Values greater than zero indicate violation of the race model. *Asterisks* indicate significant differences between the V + T (predicted VT) and (actual) VT conditions (Holm-Bonferroni correction, $p < .05$). Results for younger adults are identical to those shown in Fig. 3

studies took measures to control these parameters (e.g., Couth et al. 2016; Forster et al. 2002; Poole et al. 2015). It is true that the visual stimuli in the middle condition were slightly closer to the fixation point than those in the other conditions and that the visual angle of the visual target position decreased with an increase of the visual target distance. However, we confirmed that the distance of visual target did not affect detection performance of visual stimuli themselves for either participant group. Additionally, these differences alone could not fully account for the group differences in visuotactile interaction because the same stimulus configuration was used for all groups. The second point of the discussion is the arbitrariness of the older group classification by sensorimotor performance. With respect to the TUG test, in general, community-dwelling older adults who need 13.5 s or longer to complete this test are classified as high fall-risk (Shumway-Cook et al. 2000), although other cut-off values have been reported (16 s, Kristensen et al. 2007; 11.1 s, Whitney et al. 2004). In the present study, four older participants needed more than 10 s to complete the test, but even these individuals did not exceed 11.1 s (i.e., no one met these criteria). As for the postural stability test used in the present study (i.e., static posturography test), detailed investigations about appropriate indexes and cut-offs that can predict fall-risks have only recently begun, although the usefulness of such measures has been discussed in several studies (e.g., Howcroft et al. 2017; Visser et al. 2008). Thus, because no appropriate criterion exists for group classification, we subdivided older participants by the median of each test score and compared them. It is important to note that even older adults who showed relatively poor performance on the tests exhibited visuotactile interactions in far space. It is probable that fallers (no fallers were included in the present study) and older adults with high fall-risk even more clearly exhibit large visuotactile peripersonal space. Finally, it is unclear with the current data alone why the race model violation was not observed even in the near space in the older adults with better sensorimotor performances. It is possible that the peripersonal space was limited to a very small spatial range from the hand for those participants, while other factors affected the performance including the race model criterion the present study used (see footnote 2 in the "Results" section). More data are required to discuss this phenomenon.

We will hereafter discuss links between enhanced visuotactile interactions and decreased gait and balance functions in older adults. Previous studies found that peripersonal space was closely linked to interactions with the surrounding environment through motor actions (e.g., Làdavas and Serino 2008). Iriki et al. (1996) showed that visual receptive fields within visuotactile bimodal neurons in macaque monkeys' postcentral area were enlarged immediately after using a tool to reach an object located in far space. Fogassi et al. (1996) reported that the visual receptive fields of visuotactile neurons in area F4 expanded with an approaching visual object's increasing velocity. In humans, a similar remapping of far space as near space (as observed in monkeys) (Iriki et al. 1996) was reported in patients with RBD exhibiting extinction (e.g., Farnè and Làdavas 2000; Berti and Frassinetti 2000; Maravita et al. 2001), as well as in healthy adults (e.g., Brozzoli et al. 2009, 2010; Holmes et al. 2004; Maravita et al. 2002; see Holmes and Spence 2004 for a review). These findings suggest that peripersonal space can be dynamically changed in association with motor actions. Several studies suggest that peripersonal space representations may serve to protect the body from potential threats such as approaching objects (e.g., Graziano and Cooke 2006). Thus, older adults with relatively poor gait and balance might extend their peripersonal space to process any approaching obstacles given that they would need more time to move their whole body compared to a healthy older or younger adult. Because sensorimotor processing related to gait and posture seems to be more linked to the whole body rather than the hand alone, peripersonal representations that are not specific to the hand might have affected the participants' performance (Bloesch et al. 2013; Couth et al. 2016). This may be clarified by investigating whether visuotactile interaction can change depending on the hand position and whether the range of the peripersonal space (especially its upper limit) is indeed functional. Further, it should be noted that peripersonal space expansions in previous studies were induced by current tasks (retrieving objects placed in far space or detecting approaching objects from far space) and disappeared shortly after the tasks (e.g., Iriki et al. 1996). In contrast, our task did not require the participants to conduct any motor actions with reference to objects placed in or approaching from far space. These differences remain an open issue.

Alternatively, it is more likely that a common cause exists, rather than causal links, between enhanced visuotactile interactions and decreased gait and balance functions. Previous studies suggest that there is a decline in inhibitory mechanisms in older adults and hence they may not be able to efficiently select task-relevant information from a variety of incoming inputs (e.g., Peiffer et al. 2007; Poliakoff et al. 2006a). In the study by Polliakoff et al. (2006a), older adults exhibited more interference than young adults for visual distracters during a tactile location discrimination task. The authors argued that older adults have greater difficulty attending to a target modality while ignoring an irrelevant modality. Selecting relevant information and inhibiting irrelevant information is necessary for maintaining balance and walking, because these functions are achieved by integrating information from several sensory modalities, including vision, touch, proprioception, and vestibular system (e.g., Horak and Macpherson 1996). Additionally, the TUG test consists of several actions, such as sitting, standing, walking, and turning, requiring that participants switch tasks with proper timing. This processing also relies on attention and executive functions (e.g., Yogev-Seligmann et al. 2009). Recent studies have reported close associations between TUG performance, and attention and executive functions among older adults (e.g., Donoghue et al. 2012; Kawagoe and Sekiyama 2014). Thus, declines in attention and executive functions may indirectly contribute to enlargement of peripersonal space, as well as relatively poor TUG performance and postural stability. However, it should be noted that the present study did not find any group differences in the participants' ability for attentional control and task switching in the TMT test. Future studies should clarify details regarding attention and executive functions in old age.

A change in sensory weighting/reweighting processes among older adults is also a possible explanation for the present findings (e.g., Barrett et al. 2015; Chan et al. 2014; Horak et al. 1989; Jeka et al. 2010; Setti et al. 2011). To maintain postural stability, information from several sensory modalities has to be properly integrated. Jeka et al. (2010) investigated how large changes in visual motion stimulation amplitude affected postural stability in young, healthy older and fall-prone older adults. The authors reported that fall-prone older adults were more reliant on visual information than the healthy older and young adults were. Furthermore, older adults had slower time courses for sensory reweighting when visual motion amplitudes changed. Other studies reported that older adults exhibited greater reliance on visual information for postural control (e.g., Bugnariu and Fung

2007; Eikema et al. 2013; Yeh et al. 2014) and locomotion (Berard et al. 2012; Fraz et al. 2015). Barrett et al. (2013) reported poorer spatial-updating performance in fall-prone than in healthy older adults only when visual information was degraded. Considering these findings, especially in individuals with decreased gait and balance, sensory weighting/reweighting mechanism may rely excessively on visual information in a way that causes visuotactile interactions to occur even in the far space. If declines in sensory weighting/reweighting functions are closely associated with older adults' falls, it can be argued that training or rehabilitation programs to facilitate appropriate multisensory interactions could be effective in reducing fall risk in older adults. In fact, several studies have proposed balance training intervention as a candidate for recalibrating these mechanisms (Hu and Woollacott 1994a, b; Merriman et al. 2015).

It could also be argued that the effects observed in the present study are linked to neural dedifferentiation in older adults (e.g., Baltes and Lindenberger 1997; Geerligs et al. 2014, 2015; Park et al. 2004). Recent brain imaging studies have reported that the brain areas/networks in the older adults become less functionally distinct from those of younger adults (e.g., "dedifferentiation," Baltes and Lindenberger 1997; Geerligs et al. 2014; Park et al. 2004). This type of neural change may underlie certain patterns present in our results, namely decreased sensorimotor functions and enhanced multisensory performance observed in older adult participants.

In summary, the present study investigated the space in which visuotactile interactions emerged (visuotactile peripersonal space) for older adults and the association of this space with sensorimotor gait and balance functions. Results revealed that visuotactile peripersonal space was extended to far space in the sagittal direction for older adults. Additionally, this effect is salient for older adults with relatively poor sensorimotor functions. These results suggest that peripersonal space in older adults might be linked to their decline in sensorimotor functions related to gait and balance. Future studies should address the underlying process that links enlarged visuotactile interactions, and decreased gait and balance functions.

**Acknowledgements** This study was supported by JSPS KAKENHI Grant (S) (No. 16H06325), (A) (No. 25245068), and (B) (No. 26285160). Part of the data for this manuscript was presented at the International Multisensory Research Forum 2015.

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