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Comparison of peripersonal space in front and rear spaces

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Abstract

The space immediately around the body, referred to as the peripersonal space (PPS), plays a crucial role in interactions with external objects and in avoiding unsafe situations. This study aimed to investigate whether the size of the PPS changes depending on direction, with a particular focus on the disparity between the front and rear spaces. A vibrotactile stimulus was presented to measure PPS while a task-irrelevant auditory stimulus (probe) approached the participant. In addition, to evaluate the effect of the probe, a baseline condition was used in which only tactile stimuli were presented. The results showed that the auditory facilitation effect of the tactile stimulus was greater in the rear condition than in the front condition. Conversely, the performance on tasks related to auditory distance perception and sound speed estimation did not differ between the two directions, indicating that the difference in the auditory facilitation effect between directions cannot be explained by these factors. These findings indicate that the strength of audio-tactile integration is greater in the rear space compared to the front space, suggesting that the representation of the PPS differed between the front and rear spaces.

Keywords

Peripersonal space, Audiotactile interaction, Rear space, Auditory distance perception

Introduction

The immediate space around the body wherein physical interactions occur with objects in the surrounding environment is commonly known as the “peripersonal space” (PPS) (Rizzolatti et al. 1981a, b; Rizzolatti et al. 1997). Studies on single-cell recordings in monkeys have demonstrated that there are neurons that respond not only to tactile stimuli presented on the body surface but also to visual/auditory stimuli presented close to the body surface (referred to as visuo-tactile/audio-tactile bimodal neurons). The firing rate of these neurons decreases as the distance between the visual and auditory stimuli and the body increases (Bremmer et al. 2001; Duhamel et al. 1998; Graziano and Gross 1993; Graziano et al. 1994, 1997; Rizzolatti et al. 1981a, b, 1983, 1997, 1998). In humans, evidence for PPS has been provided by studies conducted in patients with right brain damage and healthy adults (e.g., De Paepe et al. 2016; di Pellegrino et al. 1997; Làdavas and Farnè 2004a, b; Làdavas et al. 1998a, b; Sambo and Foster 2009). Similar to studies on monkeys, the distance between a target and the body surface is crucial for humans. Visuo-/audio-tactile interactions are modulated by the distance between the stimuli and the body surface; the facilitation/interference effect of the interaction is more remarkable when the distance between the visual/auditory stimulus is close to the body surface and diminishes as the distance increases (di Pellegrino et al., 1997; Kitagawa et al., 2005; Làdavas, 2002; Làdavas et al., 1998). In these behavioral studies, the PPS was operationally defined as the space in which tactile detection was influenced by visual and/or auditory stimuli.

Previous studies have shown that potential threats from the external environment modulate the boundaries of the PPS (e.g., de Haan et al. 2016; Ferri et al. 2015; Graziano and Cooke 2006; Taffou and Viaud-Delmon 2014). For example, de Haan et al. (2016) reported that the spatial extent of the PPS, where visuotactile interaction occurs, expanded more during the approach to threatening stimuli (i.e., spiders) than to non-threatening stimuli (i.e., butterflies). Furthermore, Ferri et al. (2015) showed that sounds inducing negative emotions (i.e., brown noise) and negative ecological sounds (i.e., screaming woman's voice) expanded PPS more than sounds with a neutral or positive valence (i.e., white noise, baby laughter voice, and brush teeth sound). These findings suggest that one of the roles of the PPS is to provide a safety margin around the body.

One advantage of the auditory system is that humans can perceive sounds from various spatial directions, including those outside their visual fields. Therefore, we believe that the auditory system plays a crucial role in alert systems. Previous studies have demonstrated that the spatial location of sound sources influences emotional evaluation (e.g., Asutay and Västfjäll 2015; Frankowska et al. 2020; Hsse et al. 2014; Tajadura-Jiménez et al. 2010), as well as auditory perception and cognition performance (e.g., selective attention, time-to-contact estimation) (e.g., Asutay and Västfjäll 2015; Teraoka et al. 2023). Asutay and Västfjäll (2015) demonstrated that stronger negative emotions were elicited when sound sources were presented behind listeners as opposed to being presented in front of them. Consequently, the performance of sound source detection in terms of speed and accuracy was higher in the rear space than in the front space.

Considering the above, we hypothesized that the spatial location of sound sources also influences the extent of PPS. Specifically, as humans are more likely to perceive the rear as a potential threat, the PPS range should be larger in the rear space than in the front space to provide a defensive buffer. However, whether the PPS range is asymmetric or symmetric in all directions remains controversial (Hunley and Lourenco 2018). Previous studies have investigated the representation of PPS around the trunk, specifically between the front and rear spaces, and found that the size of PPS was the same in the front and rear spaces (Matsuda et al., 2021; Serino et al., 2015). One possible reason for this discrepancy is the methodology used to measure PPS. The aforementioned studies employed a method proposed by Canzoneri et al. (2012) in which a looming probe sound was continuously presented for several seconds while participants awaited and experienced tactile stimuli. The tactile stimuli were presented at several temporal delays from the onset of the probe sounds. Consequently, participants could be more prepared to respond to a tactile stimulus with increasing delay, thereby facilitating the tactile detection. This effect is known as the anticipation effect (Noel et al., 2015) or the expectancy effect (Holmes et al., 2020; Kandula et al., 2017). Since the range of PPS was defined by the performance of tactile detection, this could potentially hinder the anisotropy of the PPS range, depending on the direction of observation[1]. Notably, Matsuda et al. (2021), who applied Canzoneri's method, suggested that the strength of PPS differs between the front and rear spaces, even though this study concluded that the size of PPS does not differ around the body, and there was no statistical support for this. This may also be explained by the aforementioned rationale.

Our study aimed to investigate whether the boundaries of the PPS depend on direction, particularly focusing on the difference between the front and rear spaces, using a method that minimizes the anticipation effect (Kuroda and Teramoto 2021, 2022; Teramoto 2018). To minimize such an anticipation effect, in the present study, we used an approaching probe lasting 1000 ms so that the time to deliver the tactile target from the onset of the probe was constant at any distance. Participants were instructed to respond as quickly as possible to a tactile stimulus administered on their chest while task-irrelevant sounds approached the body. We examined the directional dependency of the PPS boundaries by manipulating the approaching direction (front or rear).

To appropriately evaluate the directional dependence of PPS boundaries, it is also crucial to verify whether there are differences in the perception of approaching stimuli

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[1] In some previous studies where the Canzoneri's method was employed (e.g., Serino et al., 2015), the anticipation effect was considered. For instance, Serino et al. (2015) measured the reaction time (RT) to the tactile stimulus at the nearest and farthest distances in their experimental settings; the fastest RT among them was the representative RT as the baseline. It was then subtracted from the RT of the audio-tactile stimulus at various distances. With this procedure, they attempted to remove the anticipation effect from audio-tactile integration. However, because the baseline was not measured at all possible time points, the results might differ from those of the audio-tactile stimulus presentation condition. Thus, Holmes et al. (2020) pointed out that this procedure cannot fully assess the anticipation effect (see the Discussion section for more details).

(such as sound distance and speed) between the front and rear spaces. A recent study indicated that the perception of auditory distance varies depending on whether sounds originate from the front or back owing to differential sound filtering by the pinnae and the availability of visual information (Aggius-Vella et al. 2022). Thus, participants might have perceived task-irrelevant sound stimuli approaching from the same physical distance at different locations between the front and rear spaces. Furthermore, if the perception of the auditory distance differs, it might also influence the perception of the speed of the approaching sound stimulus (as different movement distances, even with the same presentation time, yield varying perceived speeds). Several studies have shown that the speed of task-irrelevant approaching objects is influenced by the extent of PPS (Serino et al. 2015). Therefore, this study additionally examined auditory distance perception and speed perception for approaching sounds in the front and rear spaces.

Methods

The main objective of the present study was to quantitatively assess the range of audio-tactile PPS. The experimental procedure employed in this study was based on our previous research (Kuroda and Teramoto 2021, 2022; Teramoto 2018), although these studies focused on measuring visuo-tactile PPS.

Participants

Twenty-one undergraduate and graduate students (mean age: 21.14 ± 2.51 [standard deviation] years, 8 men) were recruited. The sample size required for a medium-level effect ($f = 0.25$; Cohen 1992) was calculated using G*Power (Faul et al. 2007; Faul et al. 2009). A sample size of 19 participants was required (α error probability = 0.05, power [$1-\beta$ error probability] = 0.80, repeated measures, within). Finally, we adopted 21, because we expected 10% dropouts. All participants self-reported normal hearing and touch sensations. The study design was approved by the Ethics Committee of the Faculty of Humanities and Social Sciences of Kumamoto University, and the experiments were performed following the principles of the 1964 Declaration of Helsinki. All the participants provided written informed consent before commencing the experimental session.

Apparatus and Stimuli

All experiments were conducted in a quiet room. The experimental setup is illustrated in Fig. 1. Sound stimuli were controlled using a laptop computer (Dell XPS 7390) with a MADI interface (RME MADIface USB) and a multichannel power amplifier (Innosonix MA32/LP). Octave (version 6.2.0) with an open-source audio I/O library (Playrec, http://www. playrec.co.uk/) was used for controlling the experiment. A numeric keypad was used to record the responses. Sound stimuli were presented from an array of ten loudspeakers (Aura Sound, NSW1-205-A) aligned in the depth direction. The loudspeakers closest to the participant were positioned 48 cm from the center of the participant's head, while the others were positioned at intervals of 16 cm from 64 to 192 cm. The loudspeakers were placed at chest level (110 cm). Each loudspeaker unit faced the room's ceiling so that the sound stimulus from the loudspeaker was not occluded by the other loudspeakers in front of it.

To create an approaching sound as the probe object, a pink noise burst sound stimulus was presented sequentially from four spatially consecutive loudspeakers. A cosine window was applied to the pink noise presented by each loudspeaker, and the sound pressure level used to present the pink noise from each loudspeaker was changed accordingly (Fig. 1-c). The total duration of the stimulus was 1000 ms, including 10 ms rise and fall times. Thus, the sound stimulus moved 48 cm at a speed of 48 cm/s. Three initial distances from the participants' heads were used: 96 cm (near), 144 cm (middle), and 192 cm (far). The sound pressure level was set to 70 dB for the nearest loudspeaker (48 cm), which was measured at the center of the participant's head in their absence. In other words, the sound pressure level decreased with increasing distance from the closest source.

A vibrotactile stimulator with a 0.95 cm diameter (C1034; SHICOH, Yamato, Japan) was attached to each participant's chest. It was set to vibrate at a frequency of 300 Hz, duration of 100 ms, and amplitude far above the detection threshold.

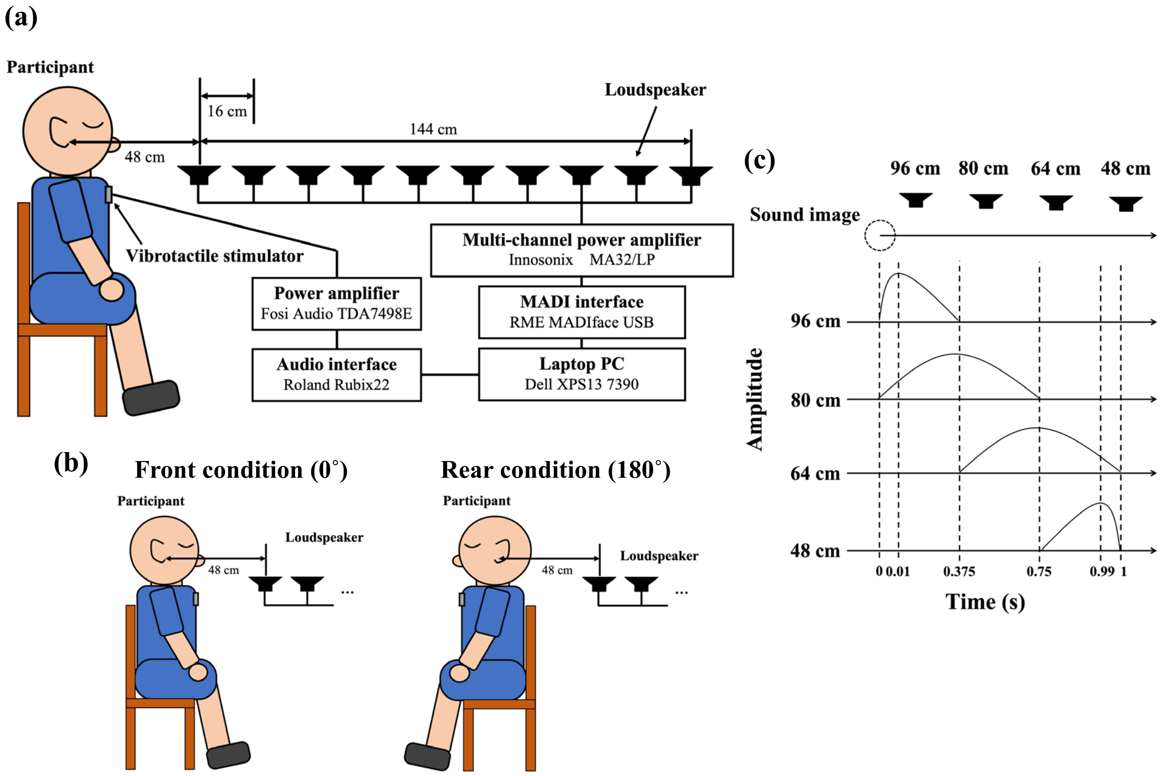

Fig. 1 (**a**) Schematic illustrations of the experimental setup, (**b**) indicating the two directions tested (0° and 180°), and (**c**) the method of generating moving sound stimuli. (**a**) Sound stimuli were presented from an array of ten loudspeakers. A probe sound appeared at several distances and approached for 1 second. Participants were asked to respond to a tactile stimulus as quickly as possible when it was presented. (**b**) Each task was carried out in two directions relative to the participant: 0° (front) and 180° (rear space). (**c**) To generate an approaching sound as the probe stimulus, pink noise bursts were sequentially presented from the four loudspeakers (the illustration shows the near condition). Each pink noise burst from the loudspeakers was processed with a cosine window, and the sound pressure level

was adjusted accordingly for each presentation.

Procedure

This experiment comprised one main task and two supplemental tasks: PPS measurement, auditory distance perception, and speed estimation tasks. Each task was performed in two directions relative to the participants: 0° (front) and 180° (rear). Each direction was performed in a different block. To control for visual information, the participants were asked to keep their heads stationary and close their eyes when sound stimuli were presented.

PPS measurement task

At the beginning of each trial, a 500 ms pure tone (frequency: 1000 Hz) was presented from all loudspeakers simultaneously to inform the start of the trial. After a one-second interval, the probe sound appeared at a specific distance (near, middle, or far) and moved toward the participant for 1000 ms. During this period, a tactile stimulus was presented at one of three different times: 250, 500, or 750 ms after the onset of the probe sound (hereafter, probe trials). Each block of trials included baseline and catch trials. Baseline trials were conducted to establish a comparison by delivering the tactile stimulation without a probe sound. The timing of the tactile stimulation in these trials coincided with the timing used in the probe trials after the presentation of the pure tone, indicating the start of the trial: 1250, 1500, or 1750 ms (i.e., the timings of the tactile stimulation were the same as those in the probe trials). These baseline trials were used to estimate the PPS boundary (see the data analysis for details). Catch trials were designed to prevent automatic motor responses to probe sounds. In some catch trials, the vibrotactile stimulation was not delivered when the probe sound was presented. In the other catch trials, probe sounds and vibrotactile stimulation were absent. The inclusion of catch trials helped ensure that the participants were actively engaged in the task and did not respond automatically to the sound stimuli. The participants were instructed to respond to the tactile stimulus as quickly as possible when it was presented. Each block consisted of 56 trials, including 36 probe trials (with four repetitions for each of the three timings and three distances), 12 baseline trials (with four repetitions for each of the three timings), and eight catch trials (with two repetitions for each of the three distances in trials with the probe and two repetitions without the probe). The order of the conditions was randomized within each block. An inter-trial interval ranging from 1000 to 1500 ms was randomly selected. Overall, participants completed a total of 112 trials. Before the main task, the participants underwent a practice session consisting of ten trials to ensure that they understood the task.

Auditory distance perception task

Each trial began with the presentation of a 500 ms pure tone. Subsequently, a 1000-ms pink noise stimulus approached the participant from a specific distance (near, middle, or far). The participants were instructed to estimate the distance of the midpoint of the sound trajectory and verbally report it in meters. Specifically, if the participants' responses were consistent with the physical distances of the sound stimuli, the responses for the near, middle, and far conditions were 0.72, 1.2, and 1.68 m, respectively. The task comprised 72 trials with 12 repetitions for each combination of two directions (front and rear) and three distances.

Speed estimation task

Each trial began with the presentation of a 500 ms pure tone. Subsequently, a 1000-ms pink noise sound stimulus approached the participant from a specific distance (near, middle, or far). The speed of the sound stimulus was manipulated into three levels: normal, fast, and slow. Under normal conditions, the speed of the sound stimulus was consistent with that in the PPS task (48 cm/s). Under fast and slow conditions, the speeds of the sound stimuli were 96 and 32 cm/s, respectively. Because the approaching distance was consistent across speed conditions, the presentation durations were 500 and 1500 ms, respectively. Participants were instructed to estimate the speed of the sound stimulus and respond verbally using magnitude estimation. The magnitude of the estimation ranged from zero to infinite. To aid in their estimations, participants were provided with the speed in the middle condition (front) as a reference. They were instructed to consider the magnitude of this reference speed to be 10 while ignoring its duration. Before the main task, participants underwent a practice session consisting of several trials. During this session, the participants familiarized themselves with the reference speed and learned how to respond accordingly. The main task consisted of 144 trials, including 12 repetitions in the normal speed condition, six repetitions in the slow speed condition, and six repetitions in the fast speed condition for each of the two directions (front and rear). The order of the trials was randomized for each participant. Only normal-speed conditions were included in the main analyses.

Data analysis

Statistical analyses were conducted using R software (version 4.1.2) and JASP (version 0.16). For the PPS measurement task, reaction times (RTs) for the probe and baseline trials were used to quantify the PPS boundaries. For the RT analysis, only trials where the RTs were within ± 3 standard deviations from the mean for each of the probe distance and baseline conditions were included. This outlier exclusion procedure for the RT was applied once per condition per participant after the data were log-transformed. The mean RTs for the probe trials (probe RTs) were calculated for each direction and distance condition, whereas the mean RTs for the baseline trials (baseline RTs), which did not include a distance variable, were calculated for each direction. Because the tactile timing variable was configured to prevent the participants from anticipating when a tactile timing was delivered and was not the main manipulation, the timings were collapsed in each of the probe and baseline RTs. Baseline RTs were subtracted from the probe RTs. Positive and negative RT difference values indicate auditory interference and facilitation, respectively. A value of zero suggests that the probe sound did not affect tactile detection.

For the RT difference, the Shapiro-Wilk test was first used to test for normality. The results rejected the normality of the data. Therefore, these data were analyzed using non-parametric methods. A comparison between conditions was performed using repeated-measures analysis of variance (ANOVA) on aligned rank-transformed data using the *ARTool* (Elkin et al. 2021; Wobbrock et al. 2011) package for R. Furthermore, to clarify the PPS boundaries, a one-sample Wilcoxon signed-rank test was performed against zero (i.e., no facilitation effect) in each direction and in each distance condition, which was defined as the farthest distance at which the RT differences were present. Multiple comparisons were conducted using Holm's correction.

The Shapiro-Wilk test revealed that all data were normally distributed for the auditory distance perception and speed estimation tasks. A two-way repeated-measures ANOVA was performed using the *anovakun* (Iseki 2020) package for R. We adjusted the degrees of freedom using Greenhouse-Geisser's epsilon when the assumption of sphericity was violated. Multiple comparisons were conducted using Holm's correction.

The auditory distance perception and speed estimation tasks were designed to test the null hypothesis; this indicated that there was no statistically significant difference between direction conditions (i.e., front vs. rear). To achieve this, Bayesian analyses were performed to assess the absence of significant differences between direction conditions. These analyses yielded Bayes Factors (BF_{01}) that provide evidence in support of the null hypothesis, varying between 0 and infinity, with values greater than 1 indicating increasing evidence for the null hypothesis.

Results

One participant was excluded because he/she did not complete all tasks. In addition, one participant was excluded because the false response rate in catch trials was more than two standard deviations above the participant's mean. Therefore, the analysis was performed on 19 participants.

PPS boundary

Figure 2 shows the RT difference (probe RT – baseline RT) as a function of distance for each direction. A two-way repeated-measures ANOVA with ART revealed significant main effects of direction (F (1, 90) = 7.85, p = .006, η_p^2 = .080) and distance (F (2, 90) = 6.61, p = .002, η_p^2 = .128), but no interaction (F (2, 90) = 0.12, p = .891, η_p^2 = .003). The main effect of direction indicated that the auditory facilitation effect was greater in the rear space than in the front space. Multiple comparisons of the effect of distance revealed a significant difference between near and far conditions (near vs. middle, p = .138, near vs. far, p = .001, middle vs. far, p = .138), indicating that the auditory facilitation effect decreased as a function of distance. One-sample Wilcoxon signed-rank tests revealed that the RT difference was significantly smaller than zero for all distance conditions in both directions (Vs $\leqq$ 4.00, ps < .001, $|r_{\mathrm{rb}}|$s = .256). These results suggest that the PPS boundaries in both directions are beyond the range measured in this study.

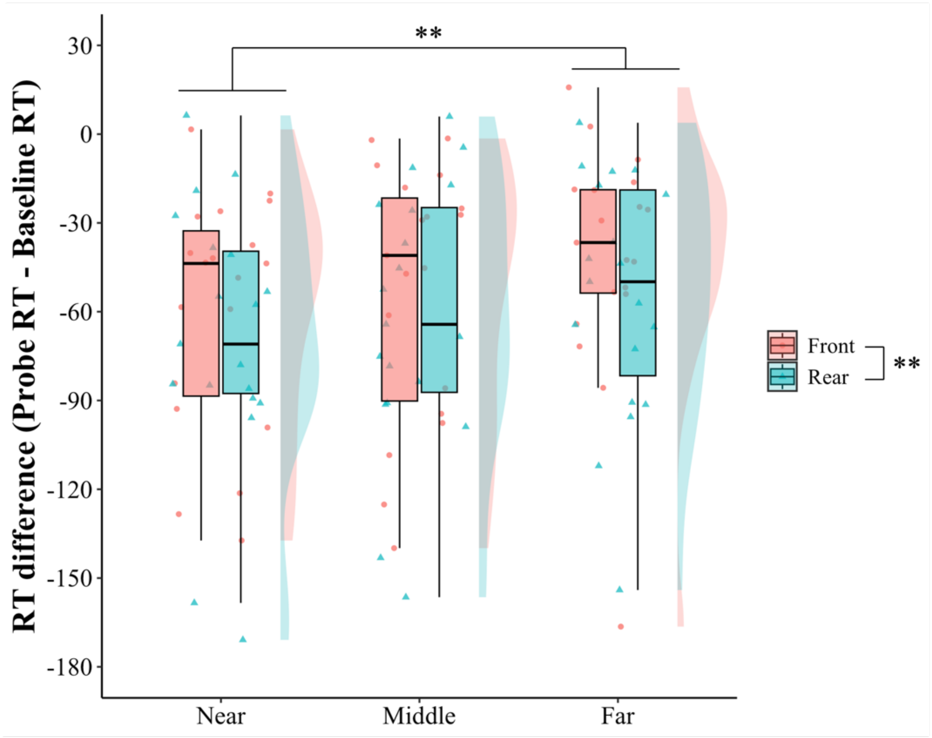

Fig. 2. Raincloud plots including individual data points, boxplots, and density functions for RT differences (probe RT – baseline RT) at each distance in each direction. Negative values indicate faster probe RT than baseline RT (auditory facilitation effect), while positive values indicate faster baseline RT than probe RT (auditory interference effect). The 95% confidence interval is indicated by the ends of the vertical error bar. Asterisks represent significant differences (* $p < .050$; ** $p < .010$; *** $p < .001$). Plots were generated using the *ggplot2* package for R.

Auditory distance perception

Figure 3 shows the mean perceived distance of the auditory stimuli as a function of the actual sound distance in each direction. A two-way repeated-measures ANOVA revealed a significant main effect of distance (F (1.15, 20.77) = 41.82, $p < .001$, $\eta_p^2 = .699$) but no effect of direction (F (1, 18) = 1.01, $p = .328$, $\eta_p^2 = .053$) or interaction (F (1.38, 24.92) = 0.27, $p = .683$, $\eta_p^2 = .015$). A multiple comparison of the effect of distance revealed a significant difference between all distance combinations (ps < .001), suggesting that perceived distance increased proportionally with an increase in the physical distance of the auditory stimuli. These results were further confirmed by the Bayesian analyses. This analysis revealed that the data supports the model that includes only the main effect of direction ($BF_{01} = 4.172 \times 10^{+7}$, % error = 4.93), indicating strong evidence for supporting the null hypothesis.

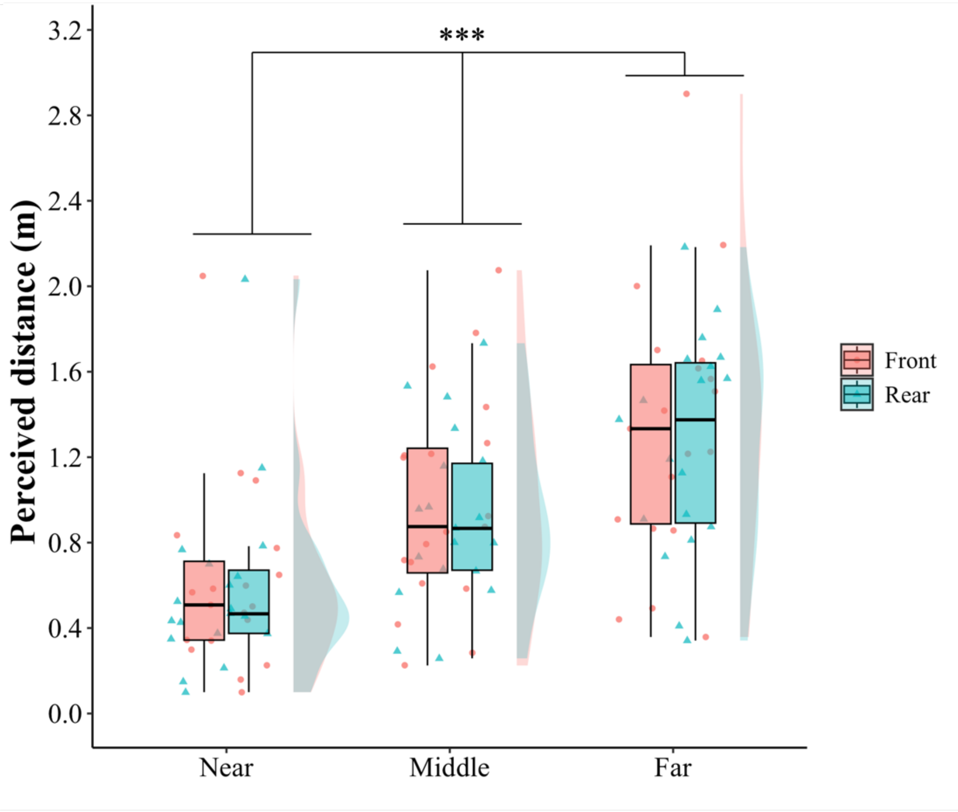

Fig. 3. Raincloud plots including individual data points, boxplots, and density functions for perceived sound distance at each physical distance in each direction. The 95% confidence interval is indicated by the ends of the vertical error bar. Asterisks represent significant differences (* $p < .050$; ** $p < .010$; *** $p < .001$). Plots were generated using the *ggplot2* package for R.

Sound speed estimation

Figure 4 shows the mean speed estimation (normal-speed condition only) in each direction (for the results of the other conditions, see the Supplementary Material). A two-way repeated-measures ANOVA revealed a significant main effect of distance (F (1.17, 21.02) = 27.54, $p < .001$, $\eta_p^2 = .605$), but not a main effect of direction (F (1, 18) = 0.44, $p = .516$, $\eta_p^2 = .024$) or interaction (F (2, 36) = 0.48, $p = .620$, $\eta_p^2 = .026$). Multiple comparisons of the effect of distance revealed significant differences for all combinations (ps < .001). This suggests that perceived speed increased proportionally with a decrease in the physical distance of auditory stimuli presentation. These results were further confirmed by the Bayesian analyses. This analysis revealed that the data supports the model that includes only the main effect of direction (BF_{01} = 725014.506, % error = 5.23), indicating strong evidence for supporting the null hypothesis.

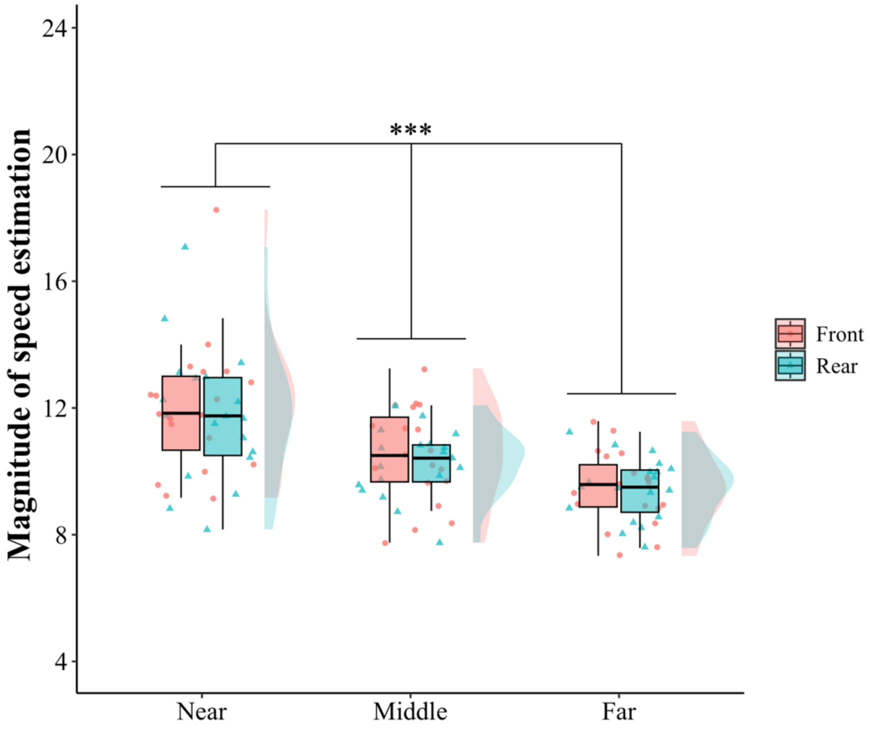

Fig. 4. Raincloud plots including individual data points, boxplots, and density functions for estimated sound speed at each distance in each direction condition. Larger values indicate that the participants perceived a faster speed of sound stimulus. The 95% confidence interval is indicated by the ends of the vertical error bar. Asterisks represent significant differences (* $p < .050$; ** $p < .010$; *** $p < .001$). Plots were generated using the *ggplot2* package for R.

Discussion

This study aimed to investigate whether the peripersonal space (PPS) boundary differs between the front and rear spaces. The results showed that the auditory facilitation effect of detecting tactile targets was significantly larger in the rear condition than in the front condition, suggesting that the strength of audio-tactile integration was not homogeneous between the front and rear spaces, with a greater degree of integration observed in the rear space compared to the front space.

While previous studies have demonstrated that the PPS extends not only in the front space but also in the rear space (Farnè and Làdavas, 2002; Graziano et al., 1999; Kitagawa et al., 2005; Van der Stoep et al., 2015), a debate remains on how the PPS is represented around the body. Previous studies that have investigated the representation of body-centered PPS (i.e., the same as the present study) have demonstrated that PPS extends equally around the body (Matsuda et al., 2021; Pfeiffer et al., 2018; Serino et al., 2015). Matsuda et al. (2021) found no statistically significant difference in the representation of the peri-trunk PPS among the directions. Hence, the authors concluded that the body-centered PPS was nearly circular. Other studies have also provided supporting evidence for this (Pfeiffer et al., 2018; Serino et al., 2015). Regarding the peri-hand PPS, however, several studies have shown asymmetrical representations. For example, Hobeika et al. (2018) investigated the size of the PPS in relation to handedness and found that the size of the PPS is larger in the left hemisphere than in the right hemisphere for right-handed participants, while it is more symmetrical for left-handed participants. Bufacchi et al. (2016) examined PPS representations around the head using the strength of the defensive blink reflex elicited by electrical stimulation of the hand (hand-blink reflex; HBR) in which participants placed their hand at various locations, such as behind or front of their head. Results revealed that the PPS extended in the front space, elongating along the vertical axis, but not in the rear. Furthermore, Matsuda et al. (2021) suggested through an exploratory analysis that the strength of PPS may differ between the front and rear spaces, although there was no statistical evidence to support this. These findings suggested that the representation of the PPS differed between the front and rear spaces. Consistent with the latter studies, the present study showed that PPS representation is not identical between the front and rear spaces.

One may argue that differences in the auditory distance perception and speed perception of probe stimuli between the front and rear spaces influence the current effect. Aggius-Vella et al. (2022) reported that auditory distance perception is more accurate in the front rather than in the rear space. Thus, the misperception of the probe in the rear space may cause an apparent difference in the PPS between the front and rear spaces. Additionally, if the perception of auditory distance differs, it could also influence the perception of the approaching sound stimulus speed (as different movement distances, even with the same presentation time, yield varying perceived speeds). However, the results of the auditory distance perception and probe speed estimation in this study showed no significant differences between the directions (front/rear) (Figs. 3 and 4). Thus, these factors do not fully explain our results.

Alternatively, different emotional impressions of the probe stimuli in the front and rear spaces may have an influence. In defensive situations, it could be advantageous to be more auditorily vigilant towards the rear space because it is not visually accessible. Given that human perceptual and action capabilities are frontward-oriented, any action in response to a threat approaching from the rear will necessarily take more time, potentially making the threat more dangerous than if it were approached from the front (Hunley and Lourenco, 2018). Indeed, previous studies have reported that the approach of threatening stimuli can expand the spatial extent of PPS compared to non-threatening stimuli (e.g., de Haan et al., 2016; Ferri et al., 2015; Taffou and Viaud-Delmon, 2014). Recent studies have also reported that stronger negative emotions (unpleasantness) can be induced by sound stimuli behind participants rather than in front of them, leading to front-rear differences in spatial localization (Aggius-Vella et al., 2020; Aggius-Vella et al., 2022), auditory selective attention (Asutay and Västfjäll, 2015), time-to-contact estimation (Teraoka et al., 2023), and emotional valence (Frankowska et al., 2020). Therefore, the results of this study may reflect this factor. However, it is not yet clear whether individuals perceive sounds coming from behind as threats. Future studies should directly examine the relationship between the size of the PPS and the subjective rating of the impression of sound. Notably, there were no differences between directions in the auditory distance perception task and speed estimation task. This may be due to the fundamentally different experimental design. Asutay and Västfjäll (2015) reported that the sound localization speed and accuracy were higher when the sound stimulus was presented from the rear space than in the front space. This difference can be explained by two factors: task and types of sound stimulus. The task that participants performed in Asutay and Västfjäll (2015) was to identify the location where the sound stimulus was presented (front or behind). Thus, the task is fundamentally different from the auditory distance perception task in the present study, which estimated the distance from the sound stimulus by fixing the direction. As for the type of sound stimulus, Asutay and Västfjäll's study used sound stimuli that evoke positive (or negative) emotion (e.g., a screaming woman's voice and a laughing baby's voice), while we used emotionally neutral stimuli. Such emotional characteristics of the sound stimuli may have accentuated the anisotropy of auditory localization speed and accuracy. For the above reasons, it may not be surprising that there was no difference between the front and rear space in these tasks.

The results of the present study are inconsistent with that of a previous study that found the size of the PPS to be narrower in the rear space than in the front space (Bufacchi et al., 2016), as well as studies that found no difference in PPS between the front and rear spaces (Matsuda et al. 2021; Serino et al. 2015). These differences might be explained by the differences in the methodology of the PPS measurements. Previous studies (e.g., Matsuda et al. 2021; Noel et al. 2015; Serino et al. 2015) employed the same PPS measurement methodology proposed by Canzoneri et al. (2012). In this method, participants awaited and experienced tactile stimuli while continuously approaching probe stimuli that were presented for several seconds (3000 ms in Matsuda et al. 2021). Tactile stimuli were delivered at several temporal delays from the onset of the probe sounds. Then, participants can expect the timing of tactile stimulation to be more prepared to respond to tactile stimuli that occur after a long delay (i.e., the anticipation effect), and consequently, it could facilitate tactile detection. Thus, if the PPS was measured by this method, it was expected that the results included not only the effect of PPS but also the effect of tactile expectation. Notably, from a visual inspection of Fig. 3 in Matsuda et al. (2021), there appears to be 30 ms – 50 ms of RT facilitation by the anticipation effect (differences in RT between the earliest and latest delay conditions). Previous meta-analysis studies revealed that the results of many previous studies, which employed Canzoneri’s method, were affected by the anticipation effect (Holmes et al., 2020). Note that previous studies that used this method considered the influence of the anticipation effect. Serino et al. (2015) included tactile-only trials (i.e., baseline trials), measured the RT for the tactile stimulus at the nearest and farthest distances in their experimental settings, and defined the fastest RT in the baseline trials as the baseline RT. Subsequently, they calculated the auditory facilitation effect as the difference between the baseline RT and average RT in each experimental audio-tactile condition. Thus, by using this procedure (which they considered as “the most conservative approach”), they attempted to remove the anticipation effect from the audio-tactile RTs. However, because the baseline was not measured at all possible time points, the results might differ from those of the audio-tactile stimulus presentation condition. A previous study indicated that this procedure cannot fully exclude the anticipation effect (Holmes et al., 2020). Thus, these differences in measurement methods may have led to differences in the results from the previous studies. Future studies should further investigate this issue.

Furthermore, differences in the type of PPS (i.e., defensive, and non-defensive) may also explain this. There are two functions of PPS: to act as defensive behaviors (e.g., avoiding threats) in relation to potentially threatening objects; and as non-defensive (e.g., interacting with objects) in relation to neutral, non-threatening objects (Bufacchi and Iannetti 2018; de Vignemont and Iannetti 2015; Hunley and Lourenco 2018). While it is more advantageous to enlarge the PPS to the rear space in defensive situations (e.g., avoiding threats), extending the PPS to the front space is more beneficial in non-defensive situations (e.g., interacting with objects) (Hunley and Lourenco 2018). Furthermore, the method employed in the present study may have elicited the defensive PPS. In the present study, the measurement of PPS involved the task-irrelevant sound stimuli approaching the participants, and participants were asked to respond to the tactile stimulus as quickly as possible. Previous studies have established that the approach of auditory stimuli, characterized by a rising sound intensity, commonly referred to as "looming," can induce feelings of threat (Bach et al., 2008; Bach et al., 2015; Neuhoff, 1998, 2001, 2016). Therefore, it is plausible that the present study measured defensive PPS, consequently influencing the representation of PPS. It should be noted that several studies employed a similar paradigm with looming stimuli (e.g., Matsuda et al., 2021; Noel et al., 2015; Serino et al., 2015) or investigated using the hand-blink reflex (HBR) (e.g., Bufacchi et al., 2016). These studies have also assessed defensive PPS, but they may not have detected the anisotropy of PPS due to their potential anticipation effects or differences in PPS representation based on the body part (e.g., trunk, vs. hand, or head).

Specific cortical processes for encoding the defensive and non-defensive PPS have been investigated in human and non-human primates by neurological studies. Previous studies demonstrated that these PPS are processed by distinct pathways. In monkeys, neural evidence suggests that defensive behaviors are represented by a parietal-premotor pathway that involves the ventral intraparietal area (VIP) and F4, whereas non-defensive behaviors are represented by a pathway that includes the anterior parietal area (AIP), 7b, and F5 (Cléry et al., 2015; Hunley and Lourenco, 2018). Furthermore, previous studies demonstrated that specific body parts may be corresponded to differentiation within these pathways. For example, the VIP and F4 are linked to the representation of the face and head, whereas the AIP, 7b, and F5 are linked to the representations of the arm and hand. This may explain the anisotropy of the PPS representations, including the present study. More attention should be paid to this topic.

The results of the sound speed estimation task showed that the perceived speed increased as the physical distance of the auditory stimulus presentation decreased, even though the speed of the sound stimulus remained the same regardless of the presented distance (see Fig. 4). There are two possible reasons: the factor of sound approaching and the underestimation of auditory distance perception. Neuhoff (2016) investigated subjective speed estimation of sounds approaching either near or far from the listener. The results indicated that listeners perceived close sounds as faster than distant sounds, even though the speed remained physically constant regardless of the distance conditions. The author interpreted this difference as related to the ability to defend oneself during an approaching threat. This factor may explain the results of the sound speed estimation task in the present study. As for the underestimation of auditory distance perception, this study suggested that the discrepancy between the veridical distance and the subjective ones (i.e., underestimation) increased as the distance increased, consistent with previous studies (Kolarik et al., 2016; Kolarik et al., 2017; Zahorik et al., 2005). Thus, the traveled distance of probe stimuli should subjectively be shorter in the far condition compared to the near condition. Since the duration of the sound stimulus is the same, the sound speed may be perceived as slower in the far condition, where the traveled distance is perceived as shorter, than in the near condition. This factor may also explain the present results. However, the more dominant factor cannot be determined from the present results; thus, this should be further investigated.

Our study has some limitations. First, the PPS boundary was not found in any condition although we used the farthest distance of 1.7 m, which was higher than that in a previous study on audio-tactile peri-trunk PPS (around 70 cm, Serino et al. 2015).

Several factors can be considered for this difference. One possible reason is the underestimation of auditory distance in the far space. Previous studies have shown that the auditory distance of the far space (over 1 m) is perceived closer than it really is (Kolarik et al., 2016; Kolarik et al., 2017; Zahorik et al., 2005). Indeed, the results of the present study demonstrated a similar tendency. This underestimation of the sound distance in the farthest distance might be associated with the unreduced influences of auditory information on tactile detection (i.e., the PPS boundary was not found). However, this cannot explain the difference in audio-tactile interaction between front and rear spaces because there was no difference in auditory distance perception between them. Thus, other factors beyond the auditory distance perception are likely associated with this issue.

Another possible reason is the probe speed. In the present study, the probe speed (48 cm/s) was determined by a combination of the constraints imposed by the size of the loudspeaker array, the methodology of the PPS measurement (e.g., the probe stimuli approached for 1 s, and multiple distance conditions were set), and the distance at which the boundary of the PPS might become apparent, based on previous studies (e.g., Noel et al. 2015; Serino et al. 2015). However, in the present study, the probe speed was higher than that used in previous studies. Neurophysiological studies in monkeys have shown that faster-looming stimuli elicit responses in PPS neurons at farther distances than slower stimuli (Fogassi et al. 1996). Serino et al. (2015) demonstrated an enlargement of PPS boundaries when audio-tactile interactions were probed with faster (35 cm/s) sounds than with slower (22 cm/s) sounds in humans. Another effective strategy may be to increase the distance condition. Previous studies that examined the peri-trunk PPS used more points and distances than the present study (e.g., Hobeika et al., 2018; Serino et al., 2015; Taffou and Viaud-Delmon, 2014). However, the distances tested in this study were only three points, and the distance range was about 2 m due to constraints related to the apparatus and experimental design. To obtain the PPS boundary, it may be necessary to conduct experiments in a virtual environment using the head-related transfer functions (HRTF). Future studies should consider these points.

Furthermore, the individual differences in the representation of PPS must be considered in this matter. Previous studies have shown that the representation of PPS is affected by individual traits, such as anxiety/phobia (Taffou and Viaud-Delmon, 2014), interoceptive accuracy (Ardizzi and Ferri, 2018), and the variance of probe stimuli (Pellencin et al., 2018; Taffou and Viaud-Delmon, 2014). Notably, a previous study has demonstrated the extent to which PPS is widely varied among individuals, ranging from approximately 50 cm to 2 m (Geers and Coello, 2023). These factors may impede the detection of the PPS boundary. Therefore, future research should also take this into consideration.

Second, there is a concern regarding the position of the vibrotactile stimulator. In the present study, the vibrotactile stimulator was always attached to the participant's chest (i.e., front side of the body) in both direction conditions. In this setup, the distance between the loudspeakers and the vibration position changes between the front and rear conditions due to the chest thickness of the participant's body (approximately 10 cm). This may not be an appropriate approach. Previous studies that examined the body-centered PPS presented the vibrotactile stimulus in a variety of ways. In Serino et al. (2015), two vibrotactile stimulators were attached to the participant's chest and back, and the stimuli were presented simultaneously. In contrast, in Matsuda et al. (2021), the stimuli were consistently presented at the participant's chest because they considered the difference in sensitivity for the vibrotactile stimulation between the chest and back (spine). Notably, a previous study has suggested that the detection performance for vibrotactile stimulation in the spine was better than in the chest (Karuei et al., 2011). Consequently, such a difference could potentially impact the results of PPS. We also presented the vibrotactile stimuli in the same way as in Matsuda et al. (2021). However, it is unclear the extent the effect of this sensitivity difference affects the performance because previous studies have not directly compared this effect. In future studies, the choice of method to use should be carefully investigated.

Third, the PPS measurement task and other tasks are different in the experimental situations. Specifically, in the latter tasks, only auditory stimuli were presented. Since these tasks were tested to confirm that these factors (distance and speed) did not affect the results of the PPS task, it might have been more appropriate to present vibrotactile stimuli in these tasks as well. Previous studies that investigated audio-tactile PPS and assessed the auditory distance perception accuracy revealed that the vibrotactile stimuli were also presented when estimating the distance of sound stimuli (e.g., Canzoneri et al., 2012; Ferri et al., 2015; Serino et al., 2015). We do not believe that a 100 ms tactile stimulus can influence auditory performance. Nonetheless, we cannot dismiss the potential impact of tactile stimulus on auditory perception. In future studies, it is imperative to evaluate the effect of tactile stimulus presence and examine the relationship between the PPS representations and the performance under tactile stimulation, should any effects emerge.

Conclusions

The present study aimed to examine the dependence of the peripersonal space (PPS) boundary on the direction, specifically focusing on the difference between the front and rear spaces. The results revealed that the auditory facilitation effect was significantly greater in the rear than in the front condition. This finding indicated that the strength of audio-tactile integration was higher in the rear space than in the front space, suggesting that the representation of the PPS differed between the front and rear spaces. It is important to note that performance in tasks related to auditory distance perception and sound speed estimation did not differ between the tested directions (front vs. rear). Therefore, these factors cannot fully explain the observed anisotropy of the PPS.

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Declarations

The datasets generated and analyzed in the current study are available from the corresponding author upon reasonable request.

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Competing interests

There is no conflict of interest.

Ethics approval

The present study was approved by the Ethics Committee of the Graduate School of Humanities and Social Sciences, Kumamoto University, and was conducted in accordance with the principles of the Declaration of Helsinki (1964).

Consent of participate (include appropriate statement)

Written informed consent was obtained from all participants before they commenced participation.

Data availability statement

The datasets generated and analyzed in the current study are available from the corresponding author upon reasonable request.

Authors' contribution

R.T, N.K, R.K, and W.T developed the study concept, contributed to the study design and data interpretation. R.T contributed to data collection and analysis, and R.K contributed to data collection. R.T, N.K, and W.T drafted the manuscript. The authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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