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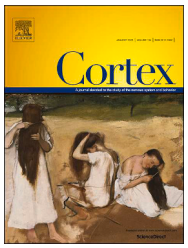

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Functional organization of distance-dependent audio-tactile integration is different in rear and front spaces

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ABSTRACT

Peripersonal space mediates animals' interactions with the environment and is thus critical for the implementation of appropriate behaviors. Integrating multisensory information located in peripersonal space induces enhanced behavioral responses and reflects the relevance of external stimuli for the organism's survival. To date, modifications of reaction time related to peripersonal space have mostly been studied using stimuli presented in the frontal space, and limited data are available on other dimensions of peripersonal space. Here, we investigated rear and front defensive peripersonal space by testing whether the distance-dependent behavioral effect of audio-tactile integration varies around the body. Healthy human participants had to detect a tactile stimulation on their hand while an irrelevant sound was approaching them from different parts of space. We used sound spatialization techniques (3D sound) to create sound stimuli looming towards participants' bodies from the front-right, front-left, rear-right, and rear-left quadrants. In the front hemifield, sounds approaching from the left had to be closer to facilitate tactile detection compared to those from the right. In contrast, in the rear hemifield, tactile detection was enhanced at similar distances regardless of whether the sound approached from the left or right. This indicates that human auditory defensive peripersonal space is not homogeneous around the body, showing a lateral asymmetry in the front but not in the rear space. This suggests that perceptual coding of space takes into account action abilities which, in humans, are driven by a front/back organization of the biomechanic skeletal system and of the sensory organs.
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1. Introduction

The auditory system allows for the detection of relevant events in the environment all around us, even those outside our field of view. As such, it plays an essential alarm function (Asutay & Västfjäll, 2015; Tajadura-Jiménez, Väljamäe, Asutay, & Västfjäll, 2010), continuously monitoring our surroundings for potential threats that could compromise our physical integrity. Studies have shown that the brain tends to treat sensory events occurring in close proximity as more behaviorally relevant than those located farther away (Blanchard & Blanchard, 2008; Mobbs et al., 2007). This aligns with the fact that short distances permit interactions. Close events can evoke interest but also pose a potential and credible threat to the body. At the neural level, events occurring near the body are processed distinctly compared to more distant events (Bernasconi et al., 2018; Cléry, Guipponi, Odouard, Wardak, & Ben Hamed, 2018; Serino, 2019) by a network of multisensory neurons whose receptive fields are anchored to specific body parts (Bremmer et al., 2001; Graziano & Cooke, 2006; Serino, Canzoneri, & Avenanti, 2011). These multisensory neurons respond both to tactile stimulation on a given body region and to other sensory stimuli depending on their distance from that body part, and particularly when the stimuli are approaching (Graziano & Cooke, 2006; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Although this phenomenon has primarily been demonstrated with visual sensory stimuli (Colby, Duhamel, & Goldberg, 1993; Gentilucci et al., 1988; Graziano & Gross, 1993, 1995), responses to auditory stimuli have also been documented (Graziano, Reiss, & Gross, 1999; Schlack, Sterbing-D'Angelo, Hartung, Hoffmann, & Bremmer, 2005). And, coherently, the presence of an auditory event close to a simultaneous tactile stimulation on the body induces behavioral multisensory integration phenomena (Farnè & Làdavas, 2002; Kitagawa, Zampini, & Spence, 2005; Làdavas & Serino, 2008; Zampini, Torresan, Spence, & Murray, 2007). The area around the body, where multisensory stimulation induce enhanced behavioral responses, is referred to as peripersonal space (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997; Serino, 2019; Van der Stoep, Serino, Farnè, Luca, & Spence, 2016).

It has been proposed that peripersonal space mechanisms fulfill at least two distinct functions (de Vignemont & Farnè, 2024; de Vignemont & Iannetti, 2015; Hunley & Lourenco, 2018): an appetitive role, which would contribute to guide goal-directed interactions with objects (Brozzoli, Makin, Cardinali, Holmes, & Farnè, 2012; Patané et al., 2019; Zanini et al., 2021), and a defensive role, which would subserve the monitoring of imminent threats (de Haan, Smit, Van der Stigchel, & Dijkerman, 2016; Ferri, Tajadura-Jiménez, Väljamäe, Vastano, & Costantini, 2015; Taffou & Viaud-Delmon, 2014) and the implementation of defensive reactions (Finisguerra, Canzoneri, Serino, Pozzo, & Bassolino, 2015; Graziano & Cooke, 2006). In one case, peripersonal space functions as a working space, serving as a privileged interface for acting on nearby objects; in the other, it operates as a protective space, providing a privileged interface for avoiding potential threats. Hearing is particularly important for the defensive function because it allows threats to be detected even when visual information is unavailable, such as in the rear space. And, the rear space constitutes a defensive weak point: unlike the frontal region, the rear hemifield is not a space of action (Viaud-Delmon, Brugger, & Landis, 2007). Implementing an appropriate behavioral response to an object approaching from behind often involves a more complex sequence of motor actions, typically requiring reorientation to face the stimulus. The distance of the stimulus—its position along the depth dimension—is a critical factor in shaping appropriate defensive behavior, especially when the stimulus is moving and decreasing its distance from the individual. The protective role ascribed to peripersonal space is linked to the possibility of performing defensive actions, which is influenced by these perceptual and motor asymmetries. Accordingly, one can expect that the auditory peripersonal space extent is not isotropic around the body and that the distance-dependent organization of audio-tactile integration differs between the front and rear spaces. Yet, no data currently clearly clarify this question.

Several studies have noted distinctions in audio-tactile integration phenomena between the nearby rear space and the nearby front space (Occelli, Spence, & Zampini, 2011; Spence, Lee, & Van der Stoep, 2017; Van der Stoep, Nijboer, Van der Stigchel, & Spence, 2015). For example, a study on brain-damaged patients showed a higher cross-modal audio-tactile extinction in the rear compared to the front space, suggesting that audio-tactile integration phenomena are more pronounced in the posterior space (Farnè & Làdavas, 2002). Moreover, audio-tactile integration is differently modulated by full body illusion in front and rear spaces (Noel, Pfeiffer, Blanke, & Serino, 2015). More recently, Teraoka, Kuroda, Kojima, and Teramoto (2024) examined how auditory stimuli looming from near, middle, or far distances influenced reaction times to tactile stimulation on the chest in healthy individuals, depending on whether the sounds were presented in the front or rear space (0° and 180°). Their results showed that looming auditory stimuli accelerated tactile detection more when presented in the rear compared to the front space (Teraoka et al., 2024) but this effect was not modulated by the distance, at which the sound source appeared. In this study, both front and rear auditory looming stimuli were aligned with participants' midsagittal plane while they were blindfolded with their head movements restricted. Sound source localization primarily relies on the assessment of interaural time and level differences (Blauert, 1997) which are unavailable under these conditions. This increases the likelihood of sound source mislocalization and front-back confusions. It therefore remains unclear whether these phenomena may have contributed to the results reported in Teraoka et al. (2024). While suggesting that audio-tactile integration consequences can differ between the rear and front space, these studies do not provide clear information about the potential anisotropy of peripersonal space extent, with distance-dependent front/back differences in audio-tactile integration.

Over the past decade, audio-tactile integration in depth has been studied to determine the distance at which an auditory event starts to be treated by the brain as particularly relevant, thereby triggering enhanced behavioral responses (Canzoneri, Magosso, & Serino, 2012; Canzoneri, Ubaldi, et al., 2013; Cardini, Fatemi-Ghomi, Gajewska-Knapik, Gooch, & Aspell, 2019; Ferri,

Tajadura-Jiménez, et al., 2015; Hobeika et al., 2018, 2019, 2020; Noel, Grivaz, et al., 2015; Serino et al., 2015; Taffou & Viaud-Delmon, 2014; Teneggi, Canzoneri, di Pellegrino, & Serino, 2013). While investigations have predominantly focused on auditory events approaching from the anterior space, with stimuli presented directly in front of the individual along the median axis or laterally, some studies have begun to examine behavioral responses to auditory events approaching from various directions around the body (Lerner, Tahar, Bar, Koren, & Flash, 2021; Matsuda, Sugimoto, Inami, & Kitazaki, 2021; Noel, Pfeiffer, et al., 2015; Serino et al., 2015). Their results did not exhibit any differences in the pattern of audio-tactile integration in depth as a function of the direction of the approaching sound. Yet, the fact that some of these studies failed to demonstrate audio-tactile integration for some of the tested directions (Lerner et al., 2021; Matsuda et al., 2021) suggest possible methodological limitations. The small range of distances tested (not farther than 1.2 m) and the slow speed of the looming stimuli (not faster than 70 $cm.s^{-1}$) in these studies may not have fully captured the dynamics of auditory processing in depth. Moreover, the rear space has mostly been investigated by using stimuli approaching from directly behind the perceiver. As previously mentioned, the use of this direction is not optimal for localization of looming auditory stimuli and front-back confusions are not systematically verified. Moreover, in the front space, evidence suggests a lateral anisotropy of peripersonal space, likely linked to individuals' action capabilities, with distance-dependent audio-tactile integration differing between the left and right sides in right-handers (Hobeika et al., 2018). Hence, a possible effect of the stimulus side, as found by Hobeika and colleagues in the front space, remains to be clarified in the rear space, as this would require the use of stimuli looming towards the body from lateralized positions. Overall, there is limited data informing us about distance-dependent audio-tactile integration in the rear space.

Distance-dependent multisensory phenomena play an important role in the interaction of the individual with the physical environment, guiding information prioritization and behavioral responses. In this respect, the interest in spatialized and multisensory information displays has grown in the field of human–system interfaces design (Bellotti, Berta, De Gloria, & Margarone, 2002; De Barros & Lindeman, 2013; Parker, Eberle, Martin, & Mcanally, 2008; Sarter, 2006; Tannen, Nelson, Bolia, Warm, & Dember, 2004; Wang, Lyckvi, Hong, Dahlstedt, & Chen, 2017). The visual channel is often overused in most interfaces. Meanwhile, 3D sound and tactile rendering technologies are becoming more accessible. Yet, to properly and efficiently exploit the advantages of theses interfaces, it is crucial to rely on the understanding of humans' multisensory space coding in all its dimensions. While cognitive neuroscience research has begun to evidence the behavioral advantages of audio-tactile signals in applied settings, such as warning displays (Gaillet, Suied, Arnold, & Taffou, 2025; Ho, Reed, & Spence, 2007; Ho & Spence, 2017; Santangelo & Spence, 2007; Spence & Ho, 2008), how the signals' position in the tridimensional space determines the behavioral benefit is not yet fully understood (Ho, Santangelo, & Spence, 2009; Kitagawa et al., 2005; Occelli et al., 2011; Teraoka et al., 2024). Although it remains unclear whether the findings from laboratory studies would hold true in more complex, real-world environments, progressing towards a more comprehensive model of 3D peripersonal space coding could offer valuable insights to enhance the design of future human–system interfaces.

To examine the defensive peripersonal space all around the body, we examined audio-tactile integration around the trunk—a body part that is not an effector but is crucial to protect from harm—using looming stimuli, which are known to activate the defensive system (Bach et al., 2008, 2009; Li et al., 2021). We used sound spatialization techniques (3D sound) to create sound stimuli looming towards right-handed participants' bodies from the front right (−45°), front left (+45°), rear right (−135°), and rear left (+135°) quadrants. These directions were deliberately chosen so as not to align with the midsagittal plane, making interaural cues informative about the position of the approaching sound sources. Moreover, a systematic screening for front-back confusions was incorporated into the procedure. To examine audio-tactile interaction around participants' bodies, we used the methodology and protocol proposed by Hobeika, Taffou, Carpentier, Warusfel and Viaud-Delmon (2020), which is based on the audio-tactile paradigm developed by Canzoneri et al. (2012). This methodology allows for examining audio-tactile integration in depth while controlling for confounding tactile expectation effects and providing a better-suited spatial sampling of measures. Because a protective space is linked to the possibility to perform protective actions, it should be linked to both perceptual asymmetries (hemispheric specialization) and motor asymmetries. Therefore, we expect the protective space to be anisotropic, depending on the motor capacities of the individual. If, as assumed, the defensive function of peripersonal space serves to monitor imminent threat to support the implementation of rapid defensive actions, then audio-tactile integration in depth—-that is, peripersonal space extent—should differ between the front (action) space and the rear (non-action) space, depending on the lateralized position (left/right) of stimuli in right-handed participants.

2. Methods

2.1. Participants

Fifty healthy participants (30 women and 20 men; age: m = 30.3 years, σ = 8.5; range [20:56]) were included in the study in order to reach a sample size of 35 participants for data analysis. Fifteen participants were not included in the analyses of the present study because they did not perceive the sound source as coming from the front hemifield in the corresponding condition. Rather they reported hearing the sound looming from the rear hemifield. This front-back confusion is a phenomenon that is commonly observed with binaural sound rendering (Wightman & Kistler, 2005) but prevent from comparing audio-tactile integration in front and rear hemifields with these participants' data. Sample size of 35 was decided a priori based on previous work examining peripersonal space boundaries with the same audio-tactile paradigm (Canzoneri et al., 2012; Hobeika et al., 2020; Serino et al.,

2015; Taffou, Suied, & Viaud-Delmon, 2021). All participants had normal hearing with audiogram thresholds at 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz being less or equal to 25 dB HL for each ear. They all reported normal touch. None of them had a history of psychiatric disorders, neurological disorders or was currently undergoing medical treatment. All of them were right-handed as assessed by the FLINDERS scale (Nicholls, Thomas, Loetscher, & Grimshaw, 2013) (all participants but four scored at +10, two participants scored at +8 and the two other scored at +9). All participants provided informed consent and were paid for their participation in the study, which was approved by the French Ethic Committee (CPP Nord-Ouest I – CPP n°2019-A01131-56).

2.2. Experimental setup and stimuli

Participants were seated on a chair positioned at the center of a well-lit room measuring 5 × 5 m with black walls. To control participants' visual stimulation and gaze direction, a fixation cross was placed on the wall in front of them, at 2.5 m distance and at eye-level. Participants' head movements were restricted through the use of a headrest.

Auditory stimuli were presented through Beyer Dynamics DT770 headphones. The auditory stimuli were sounds of 3250 msec duration composed of a bursts train (44,100 Hz digitization; see Hobeika et al., 2020). In order to simulate spatialized auditory sources, the bursts train sound was processed in Max/MSP (6.1.10) environment using the Spat library (Carpentier, Noisternig, & Warusfel, 2015). Using the same procedure as in previous work, the direct sound, early reflections and a late reverberation were simulated (Hobeika et al., 2020; Taffou et al., 2021). The spatialization of the direct sound and of early reflections was binaurally rendered using non-individual head-related transfer functions (HRTF) of the LISTEN HRTF database (http://recherche.ircam.fr/equipes/salles/listen). This procedure allows for manipulating the virtual sound source location by rendering accurate auditory cues such as frequency spectrum, intensity and interaural differences. The whole procedure was applied to the bursts train sound in order to render 8 different auditory stimuli. Half of these auditory stimuli were fixed sounds and the other half were looming sounds. In the "fixed" sound condition, the sound source remained static and located at 640 cm from participants' head center. In the "looming" sound condition, the sound source was dynamic and approached participants' head center from 640 cm to 20 cm, at ear-level and at a constant speed (210 $cm.s^{-1}$). The sound sources of the fixed and looming sounds were located in one of the four quadrants of the space around the participants: in the left hemispace of the front hemifield (azimuth 45°), in the right hemispace of the front hemifield (azimuth −45°), in the left hemispace of the rear hemifield (azimuth 135°) or in the right hemispace of the rear hemifield (azimuth −135°) (see Fig. 1).

The tactile stimulus consisted of a vibratory stimulus delivered by means of a miniature 28 mm speaker on the palmar surface of the subjects' left index finger. A sinusoidal signal was emitted for 20 msec at 250 Hz. The experimenters adjusted the vibration level so that it was easily detectable by tactile modality but not audible in silence. After each experimental block, we verified with the participants that they could perceive the tactile stimulus easily. Previous experiments have shown that when the stimulated hand is placed near the body midline and in contact with the trunk, the peri-hand peripersonal space is encapsulated in the peri-trunk peripersonal space so that the former is indistinguishable from the latter (Serino et al., 2015). Thus, in order to examine distance-dependent audio-tactile integration in relation to the trunk (and not to the hand), participants' hands were positioned palm-down on the table, uncrossed, next to each other, in contact with their bodies and aligned with their mid-sagittal plane. A PC equipped with the Presentation software was used to control the randomized presentation of the stimuli and to record the reaction times.

2.3. Procedure

Each participant completed two experimental sessions, one with the auditory stimuli located in the right and left front hemifields, and the other with the auditory stimuli located in the right and left rear hemifields. Rear and front auditory stimuli were presented in two separate sessions in order to assess potential front-back confusions. In natural situations, disambiguating whether a lateralized sound is positioned in the front or back space is typically achieved by moving the head to get interaural time and intensity differences cues. In our study, however, participants were required to keep their head immobile, leaving only spectral cues available. These spectral cues were themselves difficult to exploit, as we used binaural rendering with non-individual HRTFs—a setup known to induce front-back confusions. The use of separate sessions allowed us to verify, after each experimental block, that participants perceived all the auditory stimuli as originating from the intended hemifield. The order of presentation of the sessions was counterbalanced across the participants. The two sessions were conducted on two separate days. Participants all completed the trait portion of the State-Trait Anxiety Inventory (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983) prior to the first experimental session.

During the experimental sessions, participants were asked to press a response button with their right index finger each time they detected a tactile stimulus on their left index finger. They were asked to ignore the auditory stimulus and to respond as quickly as possible to the tactile stimulus while avoiding anticipation. Participants were also instructed to fix the permanent visual fixation cross during all the experimental blocks. We measured participants' tactile reaction times. For each trial, the auditory stimulus (fixed or looming) was presented for 3250 msec. The auditory stimulus was preceded by a 300 msec period of silence and followed by a randomly distributed period of silence between 700 msec et 1100 msec. Two types of trials were defined; experimental trials including both auditory stimulus and tactile stimulation; and catch trials consisting of instances with sound presence and an absence of tactile stimulation. The catch trials were included to decrease participants' expectation of the tactile stimulus in trials (Kandula, Van der Stoep, Hofman, & Dijkerman, 2017). For experimental trials, the tactile stimulus was presented either during the duration of the sound stimulus or during the silent period.

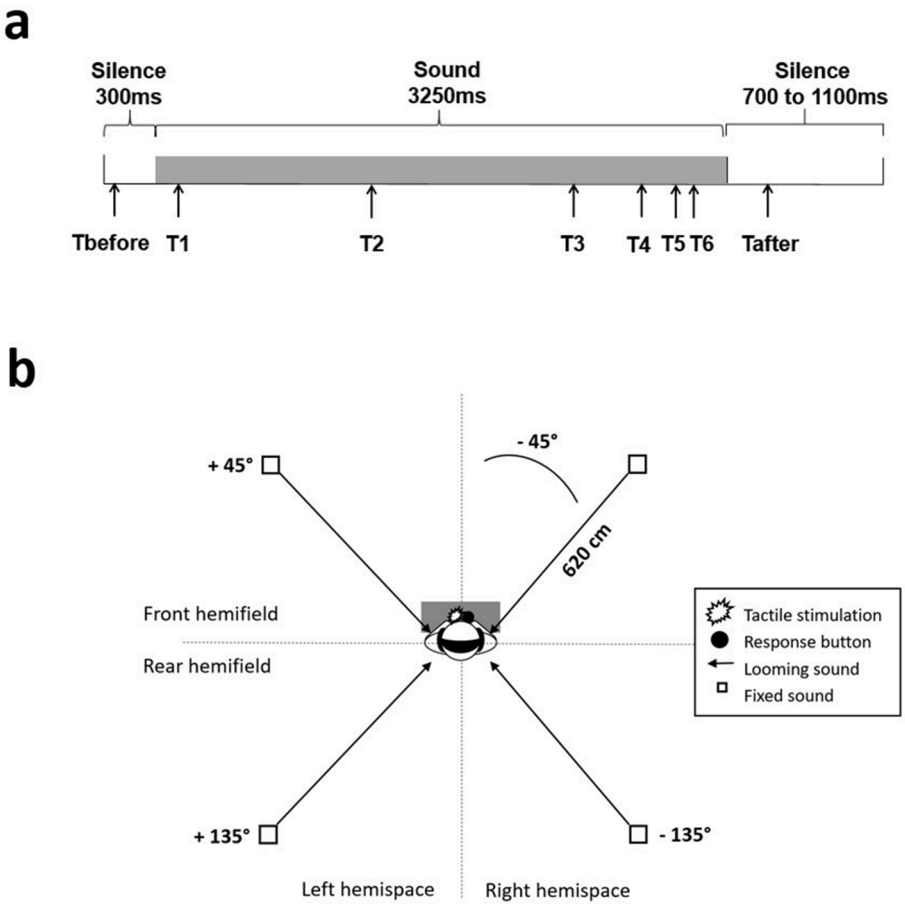

Fig. 1 – Audio-tactile interaction task. (a) Description of a trial. A trial begins with a period of silence followed by a 3250 msec-long sound and ends with a second period of silence. (b) Experimental setup. Participants were seated on a chair. Their hands were positioned palm-down on the table, uncrossed, next to each other, in contact with their bodies and aligned with their mid–sagittal plane. In this configuration the peri-hand peripersonal space is encapsulated in the peri-trunk peripersonal space so that the former is indistinguishable from the latter (Serino et al., 2015). Participants received a tactile stimulation on their left hand while a task-irrelevant sound was presented to them in either the front left (+45°), front right (−45°), rear left (+135°) or rear right (−135°) part of space. The sound could be static and located at a fixed position at 640 cm from the center of participants head (fixed sound) or looming towards participants from 640 cm to 20 cm distance (looming sound). The tactile stimulus was delivered at different delays from sound onset (Tbefore, T1, T2, T3, T4, T5, T6, Tafter). Hence, the looming sound source was perceived at different locations with respect to the body when tactile stimulation occurred, i.e. far from the body at small temporal delays and close to the body at long temporal delays.

In the experimental trials, the tactile stimuli were delivered at different times from the onset of the sound. The delay in the appearance of the tactile stimulus varied across 8 delays (−250 msec, 105 msec, 1625 msec, 2385 msec, 2765 msec, 2955 msec, 3050 msec, 3500 msec) (see Fig. 1). We also measured reaction time for unimodal stimuli (tactile without sound), delivered during periods of silence, preceding or following sound presentation (−250 msec or 3500 msec relative to sound onset), in order to establish a control baseline without integration effects. For ease of interpretation of the results, the delays were named respectively as follows: Tbefore, T1, T2, T3, T4, T5, T6, and Tafter. Tbefore represented the delay when the tactile stimulus was presented before the sound, while Tafter denoted the delay after the sound. When the auditory stimulus was a looming sound, the distance of the sound source when the tactile stimulus occurred depended on the delay between the onset of the looming sound and the delivery of the tactile stimulation—longer distances from the participant for shorter delays and shorter distances for longer delays. A spatial distribution of six different distances in depth was used. The spatial distribution followed a logarithmic scale (640 cm, 320 cm, 160 cm, 80 cm, 40 cm, 20 cm), following the recommendations of Hobeika et al. (2020). In the conditions where the sound source remained fixed and distant from participants' body, the delays between sound onset and tactile delivery were the same as in the looming sound condition, but the sound source itself remained at a far distance. This "fixed sound" condition allows for examining the effect of the expectancy of the tactile stimulus along the trial on reaction times (Hobeika et al., 2020; Kandula et al., 2017) and thus helps disentangle the spatial from the temporal effect of the sound stimulus on tactile

processing. Looming and fixed sound trials were randomly presented within each block.

In each of the front and rear hemifield experimental sessions, participants were asked to perform 20 experimental blocks of 3-min duration. Between each block, participants were allowed a 1-min break, and a mandatory 10-min break was imposed halfway through the experimental blocks. Each block was composed of 32 experimental trials and 8 catch trials. In total, participants performed 1600 trials, 1280 experimental trials and 320 catch trials (20 % of catch trials). They performed 20 repetitions for each of the 64 experimental conditions: 2 SOUND MOVEMENT (fixed/looming), 2 HEMIFIELD (front/rear), 2 HEMISPACE (left/right), and 8 DELAY (Tbefore, T1, T2, T3, T4, T5, T6, and Tafter).

3. Results

3.1. Participants

Fifteen participants were not included in the analyses of the present study because they did not perceive the sound source as coming from the front hemifield in the corresponding condition. One participant was excluded from the analyses because their score on the trait portion of the STAI stood out from the scores of our sample of participants (m = 34.7 ± 8.0; n = 35) and indicated high trait anxiety level (62; score range on STAI being [20–80]) that could potentially influence multisensory processing and peripersonal space coding (Sambo & Iannetti, 2013; Viaud-Delmon, Berthoz, & Jouvent, 2002, 2011). These exclusion criteria were established prior to data analysis. The analyses were conducted on the 34 remaining participants (17 women and 17 men; age: m = 30.4, σ = 9.0, range [20:56]; trait STAI score: m = 33.9, σ = 6.5, range [23:53]).

3.2. Audio-tactile interaction task results

The processing of the data collected during the experiment was similar to the one conducted in previous studies (Hobeika, Taffou, & Viaud-Delmon, 2019; Taffou et al., 2021; Taffou & Viaud-Delmon, 2014). Similar to the preceding experiments, participants demonstrated a high level of accuracy in performing the tactile detection task, as indicated by the low rate of misses in experimental trials (.34 %) and low rate of false alarms in catch trials (.75 %). Consequently, the analysis focused on reaction times (RTs). RTs shorter than 100 msec and longer than 1000 msec were removed from the analyses (.42 % of the trials) as we considered these RTs to be either too short or too long to accurately reflect participants' performance in the speeded tactile detection task. This exclusion criterion was established prior to data analysis. The distribution of participants' RTs exhibited skewness, a common feature in RT data (Ulrich & Miller, 1993; Whelan, 2008). To address this, we applied a natural logarithm transformation to each RT data before proceeding with subsequent statistical analyses on mean RTs (Whelan, 2008).

Our objective was to determine the distance from which the sound source started to interact with the processing of the tactile stimulus, enhancing participants' RTs in each of the four tested spatial regions. As previously mentioned, tactile expectation effects can also lead to a reduction in RTs, potentially complicating the interpretation of audio-tactile interaction effects in looming sound conditions. In the fixed sound condition of the protocol, the sound source remained static and fixed at a far distance from the participants throughout the entire trial. This 3250 msec-long sound provided a temporal reference, aiding participants in predicting and expecting the occurrence of a tactile stimulus during the trial. However, in this condition, there is little to no audio-tactile integration, as the sound source remains at a far distance from participants' body. Therefore, this condition allows for the exploration of the effect of tactile expectation on participants' RTs (Hobeika et al., 2020; Kandula et al., 2017), a factor we aimed to distinguish from the impact of audio-tactile interaction on participants' RTs. In a first step, we verified that beyond expectancy effects, we also observed audio-tactile interaction effects on tactile RTs in the looming sound condition. To do so, we examined whether the delay of tactile stimulation had a different influence on tactile RTs when the sound source was fixed or when it was looming.

3.2.1. Audio-tactile interaction and expectancy effects

With this first step of analyses, we aimed to verify that the RT data exhibit the typical pattern of an audio–tactile interaction task, with a decrease in RTs at longer delays that cannot be accounted for by expectancy effects. We averaged ln(RT) separately for each hemifield (front/rear), each hemispace (left/right), each sound type (fixed/looming) and each delay condition (Tbefore, T1, T2, T3, T4, T5, T6, and Tafter). We then conducted an ANOVA on the mean ln(RT)s with the within-subject factors HEMIFIELD (two levels: front/rear), HEMISPACE (2 levels: left/right), SOUND TYPE (2 levels: fixed/looming) and DELAY (8 levels: Tbefore, T1, T2, T3, T4, T5, T6, and Tafter). The analysis revealed a significant main effect of SOUND TYPE [$F(1,33) = 88.2$, $p < .001$, $\eta p2 = .728$] and of DELAY [$F(7,231) = 100.8$, $<.001$, $\eta p2 = .753$] as well as a significant effect of their interaction SOUND TYPE*DELAY [$F(7,231) = 23.2$, $p < .001$, $\eta p2 = .413$]. This result indicates that participants' tactile RTs were differently influenced by the delay of tactile stimulation as a function of whether the sound source was fixed or looming towards them.

As shown on Fig. 2, the data exhibited a pattern similar to the data observed in previous studies using the same audio-tactile paradigm (Canzoneri et al., 2012; Hobeika et al., 2020). In the looming sound condition, RTs for tactile stimuli at both Tbefore and T1 were not significantly different from each other ($p = .419$) and were significantly longer than RTs for tactile stimuli at T2, T3, T4, T5, T6 and Tafter (Newman–Keuls tests: $p < .001$ in all cases). Additionally, RTs significantly decreased between T2 and T3 ($p < .001$), T3 and T4 ($p < .001$), T4 and T5 ($p = .002$) and T5 and T6 ($p = .009$). RTs at Tafter were longer than RTs at T3, T4, T5 and T6 ($p < .001$ in all cases) and shorter than RTs at T2 ($p < .001$). In the fixed sound condition, RTs for tactile stimuli at both Tbefore and T1 were not significantly different from each other ($p = .972$) and were significantly longer than RTs for tactile stimuli at T2, T3, T4, T5, T6 and Tafter (Newman–Keuls tests: $p < .001$ in all cases). RTs significantly decreased between T2 and T3 ($p < .001$) and between T3 and T4 ($p = .011$). Then, RTs at T4

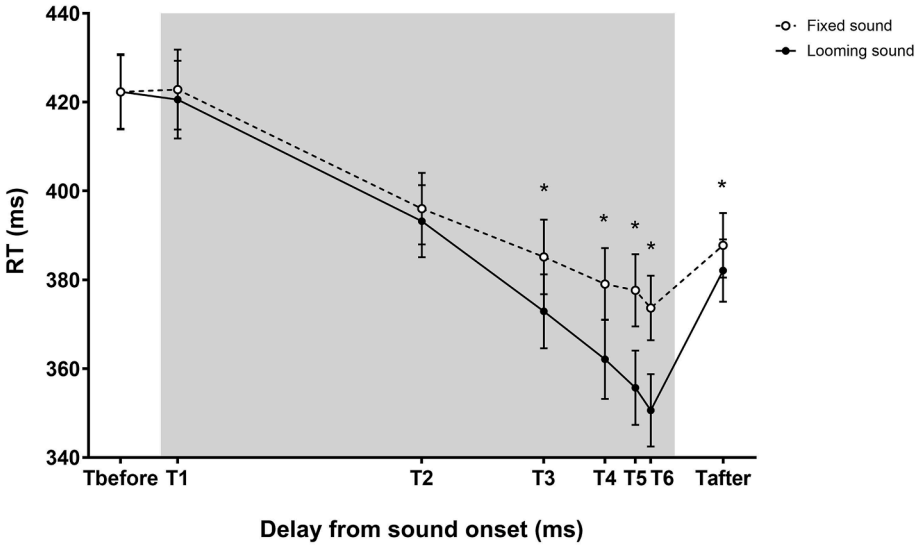

Fig. 2 – Audio-tactile interaction and expectancy effects on RTs–This figure depicts the mean tactile RTs (±SEM) of participants' (n = 34) as a function of the delay in tactile stimulation delivery from the onset of either the distant fixed sound source (filled white circles) or the looming sound source (filled black circles). In the fixed sound source condition, the sound source remained positioned at 640 cm from the participants' head center for 3250 msec, regardless of the delay at which tactile stimulation occurred. In the looming sound source condition, the sound source approached participants' head center during the 3250 msec. When tactile stimulation occurred, the sound source was far from participants at short delays and closer for longer delays. Tactile stimulation was also presented before the start of the sound (Tbefore) and after the offset of the sound (Tafter). The shaded region represents the duration of the sound. Asterisks indicate significant differences in RTs between fixed sound and looming sound conditions (*). The data exhibit a typical pattern of audio-tactile paradigm data with a decrease of tactile RTs when the looming sound source is approaching closer to the body. This acceleration of tactile RTs cannot be fully accounted for by tactile expectancy effects (observed in the fixed sound condition) but rather by both audio-tactile integration and expectancy effects.

were not significantly different from RTs at T5 ($p = .499$) and RTs at T5 were not significantly different from RTs at T6 ($p = .082$). RTs at Tafter were longer than RTs at T4, T5 and T6 ($p < .001$ in all cases) and not significantly different from RTs at T2 ($p = .123$). Crucially, RTs in the looming sound condition were shorter than RTs in the fixed sound condition for late delays T3, T4, T5 and T6 ($p < .001$ in all cases). They were not significantly different from each other at delays Tbefore, T1 and T2 ($p > .162$ in all cases). RTs at Tafter were shorter in the looming than in the fixed sound condition ($p = .025$). As hypothesized, results suggest that the temporal reference provided by the sound had an effect on tactile RTs. Critically, they indicate that the acceleration of tactile detection observed when the sound source was close to participants cannot be fully accounted for by the tactile expectancy effects but rather by both audio-tactile integration and expectancy effects.

The ANOVA also revealed a significant effect of the interaction HEMIFIELD*HEMISPACE on mean ln(RT)s [$F(1,33) = 6.65$, $p = .015$, $\eta p2 = .168$] suggesting that the side from which the sound source approached (left/right) influenced tactile RTs as a function of whether it approached from the front or from the rear hemifield. While tactile RTs to looming sounds were shorter when the sound was looming from the right hemispace as compared to the left hemispace in the front hemifield (Newman–Keuls tests: $p = .018$), they did not significantly differ between left and right hemispaces in the rear hemifield ($p = .253$). This suggests that tactile RTs were differently influenced depending of the part of space around the body in which the sound source was positioned.

To further investigate audio-tactile integration in the different parts of space around the body, we isolated the effects of audio-tactile integration from expectancy effects on RTs and kept only the multisensory delay conditions (excluding Tbefore and Tafter) in the following analyses.

3.2.2. *Audio-tactile integration around the body*

3.2.2.1. Analysis of mean RTs. With this second step of analyses, we aimed to test whether distance-dependent audio-tactile integration differs as a function of the tested direction. To isolate the impact of audio-tactile integration from expectancy effects on RTs, we subtracted from each data point in the looming sound condition the mean ln(RT) measured in the corresponding condition with the fixed sound. We then averaged the Δln(RT) for each hemifield (front/rear), each hemispace (left/right) and each delay condition (T1, T2, T3, T4, T5, T6) independently. We conducted a Student's t-test for each condition, comparing the mean Δln(RT) to 0. Δln(RT) significantly lower than 0 indicates that the sound impacted the tactile processing, resulting in accelerated RTs. Benjamini and Hochberg correction (Benjamini & Hochberg, 1995) was applied to address multiple testing concerns. The findings, depicted in Fig. 3 (for clarity, Δ(RT) instead of Δln(RT) are plotted on the figure), revealed that when the sound came

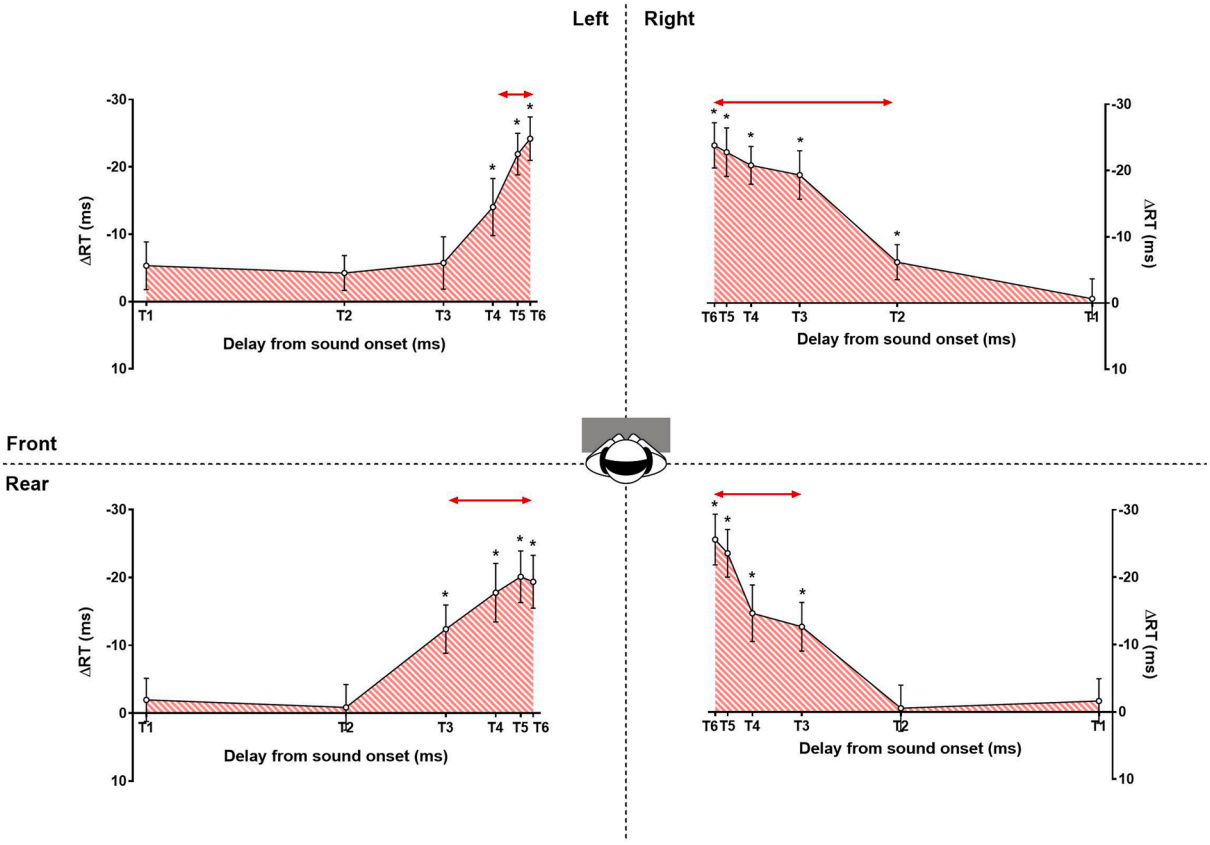

Fig. 3 – Audio-tactile interaction around the body–Analysis of mean tactile RTs. (a) This figure illustrates participants' (n = 34) reduction in tactile RT (ΔRTs ± SEM) associated with the looming sound source across the different delays of tactile stimulation delivery from sound onset. The proximity of the sound source to participants' body differed, with the farthest position at T1 (the shortest delay between tactile stimulation and sound onset) and the closest position at T6 (the longest delay between tactile stimulation and sound onset). The upper graphs present data for the front hemifield (sound source approaching from either the left or right). The lower graphs display data for the rear hemifield (from either the left or right). When Δln(RT) significantly deviates from 0 – indicated by the increasing red dashed surface and the asterisks (*) – it signifies an interaction between the sound and tactile processing, resulting in accelerated RTs. Red arrows indicate the range of delays, and, thus, distances for which the sound interacted with tactile processing and significantly speeded up participants' tactile RTs. In the front space, the sound had to approach closer from the left side than the right to initiate tactile detection enhancement. However, in the rear space, the sound source speeded tactile RTs from similar distances onward, regardless of the approach side.

from the front left, it speeded up tactile detection from T4 to T6 ($p < .001$ in all cases). When the sound came from the front right, it speeded up tactile detection from T2 to T6 ($p < .041$ in all cases). Additionally, when the sound came from the rear left or right, it accelerated tactile detection from T3 to T6 ($p < .003$ in all cases).

We then conducted two separate analyses of variance (ANOVAs) on Δln(RT) focusing on each hemifield (front and back). The within-subject's factors included HEMISPACE (2 levels: left/right) and DELAY (6 levels: T1, T2, T3, T4, T5, T6). In the front hemifield, the ANOVA revealed a main effect of DELAY [$F(5,165) = 20.13$, $p < .001$, $\eta p2 = .379$] and a significant HEMISPACE*DELAY two-way interaction [$F(5,165) = 2.30$, $p = .048$, $\eta p2 = .065$]. Specifically, on the left, Δln(RT) exhibited a significant decrease between T3 and T4 (Post-hoc Newman-Keuls: $p = .005$; Δ(RT) at T3: $IC_{95} = [-13.6 : 2.2]$; Δ(RT) at T4: $IC_{95} = [-22.7: -5.4]$), while on the right the first significant decrease occurred between T2 and T3 ($p = .001$; Δ(RT) at T2: $IC_{95} = [-11.6: -.8]$; Δ(RT) at T3: $IC_{95} = [-26.8: -11.9]$). A comparison of tactile detection enhancement between the left and the right conditions revealed that Δln(RT) at T3 was significantly lower when the sound originated from the right as compared to the left ($p = .003$). For all the other delays of tactile occurrence, there were no significant differences in Δln(RT) based on whether the sound source was on the left or right ($p > .196$ in all cases). This suggests that in the front space, the looming sound initiated tactile detection enhancement at different delays (i.e. at different distances) depending on whether it approached from the left or right. When looming from the left, the sound had to come closer to the body to start boosting tactile detection compared to when looming from the right.

In the rear hemifield, the ANOVA revealed a significant main effect of DELAY [$F(5,165) = 19.03$, $p < .001$, $\eta p2 = .366$]. However, the HEMISPACE*DELAY two-way interaction was

not significant ($p = .631$). When the sound came from the rear space, be it from the left or right side, Δln(RT) exhibited a significant decrease between T2 and T3 ($p = .003$; Δ(RT) at T2: $IC_{95} = [-5.6 : 4.2]$; Δ(RT) at T3: $IC_{95} = [-18.1: -6.9]$). There was no difference in Δln(RT) between T1 and T2 or between T3, T4, T5 and T6 ($p > .079$ in all cases). This suggests that in the rear space, the looming sound initiated tactile detection enhancement at similar delays (i.e. at similar distances) whether it approached from the left or right.

3.2.2.2. Analysis of the distribution of RTs. The large number of trials in our experiment allowed for a more detailed analysis of our effects with a distributional RTs analysis. RT distributions contain indeed far more information than is adequately summarized by their means (Schwarz & Miller, 2012), revealing how the effects of the experimental conditions impact RTs from fast to slow ones. We conducted a distributional RT analysis (Taffou et al., 2021) to assess whether the mean differences identified in the previous analysis between the effect of looming and fixed sound sources were supported by differences in the distribution of RTs. We used the algorithm and MATLAB code described by Ulrich and colleagues (Ulrich, Miller, & Schröter, 2007) to compute the average cumulative density function (CDF) of RTs for each delay condition, sound movement condition, and portion of space tested. First, empirical CDFs were estimated for each participant based on delay, sound movement, hemispace, and hemifield conditions. Percentile values were then computed from these empirical CDFs., using ten bins from the .05 percentile to the .95 percentile with an increment of .1. The resulting RT percentile values for each of the ten bins were aggregated across participants to obtain the average CDF, reflecting the distribution of participants' RTs. These CDFs, along with corresponding delta plots, are presented in Figs. 4 and 5 for each sound movement (fixed sound or looming sound) and for delays T2, T3 and T4 (CDFs and delta plots for the delays T1, T5 and T6 are available in the appendix). Delta plots facilitate the visual comparison of two CDFs representing the difference between RT percentile values in the two experimental conditions (i.e. the horizontal separation of the two CDFs) on the ordinate, against the mean of the RT percentile values in the two experimental conditions, on the abscissa (Schwarz & Miller, 2012).

To compare RT distributions between fixed and looming sound conditions, we performed bin by bin paired t-tests on RT percentile values for each delay and portion of space tested, separately. We used the Benjamini-Hochberg correction to control for multiple testing (Benjamini & Hochberg, 1995).

In the front left condition, no significant differences between CDFs were observed for delay T1. For delays T2 and T3, RT values were shorter for the looming compared to the fixed sound condition at specific percentiles (.45, .55 at T2: $p < .045$; .25, .35 and .45 at T3: $p < .029$). In contrast, marked differences were observed for delays T4, T5 and T6, where RT percentiles were consistently smaller for the looming compared to the fixed sound condition (T4, percentiles from .05 to .65: $p < .003$; T5, all percentiles except .95: $p < .001$; T6, all percentiles: $p < .002$).

In the front right condition, no significant differences between CDFs were observed for delay T1 and T2. In contrast, for delays T3, T4, T5 and T6, RT percentiles were consistently smaller for looming compared to the fixed sound condition. This pattern was observed across all percentiles at T4 ($p < .044$), and all percentiles except for .95 at T3, T5 and T6 ($p < .004$).

In the rear left condition, no significant differences between CDFs were observed for delay T1 and T2. In contrast, for delays T3, T4, T5 and T6, RT percentiles were smaller for looming compared to the fixed sound condition (T3, RT percentiles from .35 to .85: $p < .008$; T4, T5 and T6, all percentiles except for percentile .95: $p < .003$).

In the rear right condition, no significant differences between CDFs were observed for delay T1 and T2. In contrast, for delays T3, T4, T5 and T6, RT percentiles were consistently smaller for the looming compared to the fixed sound condition (T3, percentiles from .05 to .65: $p < .012$; T4, all percentiles except for .95: $p < .029$; T5 and T6, all percentiles: $p < .003$).

4. Discussion

We investigated whether distance-dependent audio-tactile integration differs in the front and rear spaces as a function of the lateral position of the auditory stimulus. Specifically, we examined tactile detection facilitation by sound sources approaching healthy participants' bodies from either the right or left in the front and rear hemifields. Our results revealed that distance-dependent audio-tactile enhancement of behavioral responses was influenced by the portion of space from which the sound source was approaching. In the front hemifield, sounds approaching from the left had to be closer to facilitate tactile detection compared to those from the right. In contrast, in the rear hemifield, tactile detection was enhanced at similar distances regardless of whether the sound approached from the left or right. Thus, audio-tactile integration in depth was modulated by the lateral position of the sound source in the front space, but not in the rear space.

Only a small number of studies have examined audio-tactile integration in depth in both the front and rear hemifields (Matsuda et al., 2021; Serino et al., 2015). In their study, Serino et al. (2015) investigated peri-trunk peripersonal space by examining how RTs to tactile stimuli were modulated by the distance of sound sources looming either from the front or the rear space in participants' midsagittal plane. Their results did not reveal any difference in peripersonal space extent between the two directions (Serino et al., 2015). Yet, as mentioned earlier, the cardinal looming sound directions they used are not optimal for localizing sounds approaching from the front versus the rear. Front–back confusions may have contributed to the absence of a significant effect of sound direction on audio-tactile integration in depth. Matsuda et al. (2021) studied peri-trunk peripersonal space using the same audio-tactile protocol and also cardinal looming sound directions (sound sources looming either from the front or the rear space in participants' midsagittal plane, or the left and right side in the coronal plane). Their analyses did not reveal different patterns of audio-tactile integration in depth across the four directions (Matsuda et al., 2021), which may also be linked to front-back confusions in sound localization. Moreover, when they analyzed the four directions separately, they did not observe the typical pattern of audio-tactile facilitation associated with peripersonal space in the rear and right directions. Thus, it

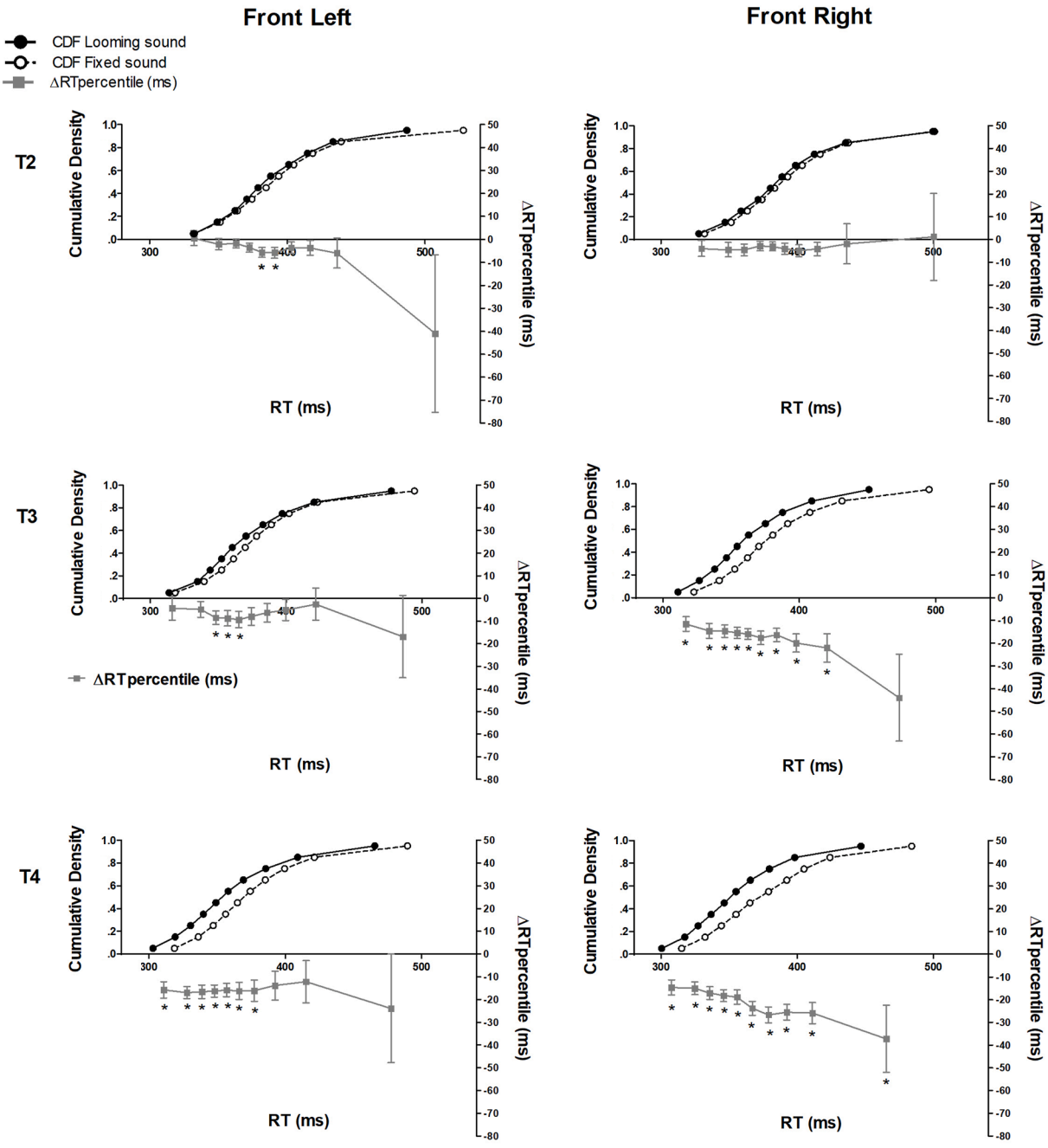

Fig. 4 – Audio-tactile interaction experiment results—Analysis of reaction times (RTs) distribution for the front hemifield condition. This figure depicts the average cumulative density function (CDF) of RTs for participants (n = 34) at delays T2, T3, T4 (from top to bottom), in the front left (left) and right (right) hemispaces, under looming (black circles) and fixed (white circles) sound conditions. To ease the visual assessment of the horizontal separation between the two CDFs, the mean difference in RT percentile values between the looming and fixed sound conditions (ΔRTpercentile ± SEM) is also displayed (grey squares). At delay T2, no notable difference is observed in RTs distribution between the looming and fixed sound conditions in either the front right or front left hemispaces. At T3, in the right hemispace, participants' fastest RTs were quicker in the looming compared to the fixed sound condition. In contrast, in the left hemispace, there is no significant difference in RTs distribution between the looming and fixed sound conditions. At T4, participants' fastest RTs were quicker in the looming compared to the fixed condition in both the left and right hemispaces. Significant differences are indicated with an asterisk (*).

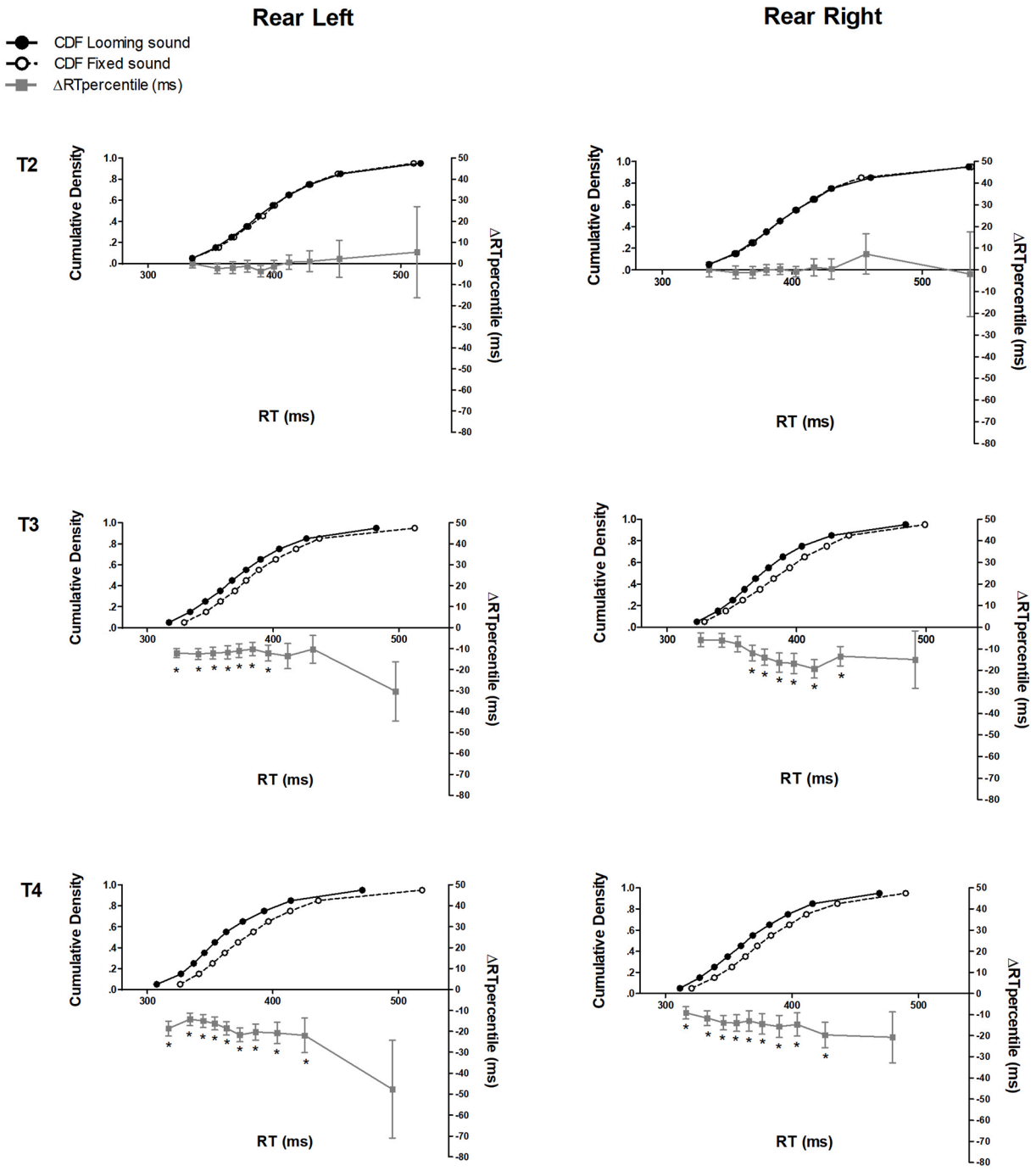

Fig. 5 – Audio-tactile interaction around the body—Analysis of reaction times (RTs) distribution for the rear hemifield condition. This figure depicts the average cumulative density function (CDF) of RTs for participants (n = 34) at delays T2, T3, T4 (from top to bottom), in the rear left (left) and right (right) hemispaces under looming (black circles) and fixed (white circles) sound conditions. To ease the visual assessment of the horizontal separation of the two CDFs, the mean difference in RT percentile values between looming and fixed sound conditions (ΔRTpercentile ± SEM) is also displayed (grey squares). At delay T2, no significant difference is observed in RTs distribution between looming and fixed sound conditions in either the rear right or rear left hemispaces. At T3 and T4, on both hemispaces, participants' RTs are generally faster in the looming compared to the fixed sound condition. Significant differences are indicated with an asterisk (*).

remains unclear whether their findings reflect a genuinely homogenous peripersonal space or whether their setup and protocol failed to capture peripersonal space extent in these directions. Nevertheless, even if these findings reflect a true absence of differences across the tested directions, they are not necessarily contradictory to ours. In both Matsuda et al. (2021) and Serino et al. (2015) studies, the sound sources approached along participants' mid–sagittal plane, which prevented any investigation of the effect of the lateralized position of the sound source. Yet, it is precisely the lateral asymmetry of audio-tactile integration in depth that differs between the front and rear spaces in the present study.

The different processing of auditory events as a function of their position in front of or behind the body could be linked to the fact that the rear space, unlike the front, is not typically a space of action (Viaud-Delmon et al., 2007). Actions are generally executed in front of the body. Growing evidence suggests that multisensory events within proximity modulate neural activity in human premotor cortex regions (Basile et al., 2024; Bernasconi et al., 2018; Ferri, Costantini, et al., 2015). At the behavioral level, the distance-dependent integration of an external sensory event and a tactile event on the body is influenced by movement execution (Brozzoli, Pavani, Urquizar, Cardinali, & Farnè, 2009; Noel, Grivaz, et al., 2015) and by motor abilities (Bassolino, Serino, Ubaldi, & Làdavas, 2010; Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013; Canzoneri, Ubaldi, et al., 2013; Hobeika et al., 2018). Peripersonal space is thus believed to play a key role in action implementation (de Vignemont, 2021; Finisguerra, Maffongelli, et al., 2015; Serino, 2016), by reflecting the behavioral relevance of actions towards external events in proximity (Bufacchi & Iannetti, 2018) and facilitating rapid and precise motor reactions. Yet, most of this research has focused on the front peripersonal space.

Our findings indicate that the distance-dependent relevance of auditory events varies depending on the side of approach in the front space, but not in the rear space. The absence of asymmetry in the rear space could be explained by the reduced contribution of motor aspects to the coding of the relevance of events located behind the body. In the front space, the lateral position of events directly impacts the efficacy of motor reactions. In contrast, in the rear space, lateral position is likely less important, as the initial motor response would typically involve turning to face the event.

Coherently, we did not observe a lateral asymmetry of defensive peripersonal space when the sound sources approached participants from the rear hemifield. In line with previous research, audio-tactile integration in depth was not influenced by the lateral position of the auditory source in the rear space (Taffou & Viaud-Delmon, 2014). Furthermore, we found a symmetrical pattern in the rear space while observing an asymmetrical pattern in the front space using the same sound stimuli with the same participants.

In the front space, an asymmetrical pattern of audio-tactile integration in depth—although reversed—was also observed in a previous study (Hobeika et al., 2018). This discrepancy is likely due to differences in the valence of the auditory stimuli used; whereas the earlier study employed bursting bubbles with a positive valence, our study used burst trains of white noise, which have a negative valence (as indicated by reports of induced discomfort even for sources at far distances, see Hobeika et al., 2020). Neither study found a main effect of the sound source side on tactile detection. Indeed, the increase of response speed is not solely linked to the side on which the stimulus occurs but instead depends on its distance. Therefore, the asymmetrical pattern cannot be only attributed to spatial compatibility or hemispheric dominance effects. Rather, in the front space, the asymmetry in distance-dependent processing of sound sources appears to adapt to the emotional context. Previous studies have also observed that affective looming stimuli modulate distance-dependant visuo- and audio-tactile integration (de Haan et al., 2016; Ferri, Tajadura-Jiménez, et al., 2015; Taffou & Viaud-Delmon, 2014). These studies consistently reported an increase of peripersonal space extent with negative compared to positive stimuli, which may be mediated by a modulation of the receptive fields of the multisensory neurons when a potential threat is appraised by cerebral structures of the defensive system (Cléry & Ben Hamed, 2021). All of these studies investigated the emotional modulation of peripersonal space in conditions in which the influence of perceptual and motor asymmetries cannot be revealed (sounds looming toward the hand, toward the trunk along the midsagittal plan or from the rear space). The findings of the present study, together with those of Hobeika et al. (2018), both of which used lateralized looming sounds in the front space, suggest that the affective valence of stimuli modulates the left and right portion of the front defensive peripersonal space differently. This asymmetrical effect would be consistent with the idea that the coding of imminent threat takes into account our ability to react to it. Given that all participants were right-handed, it is plausible that this effect reflects a lateralized bias in the relevance of stimuli for performing protective actions. Future research should clarify these asymmetrical modulations of defensive peripersonal space by examining the effects of stimuli of different emotional valences on lateral peripersonal space within the same sample of participants.

The observed patterns of audio-tactile facilitation as a function of sound direction may include a contribution of attention. While visuospatial attention is biased toward the left, there is evidence suggesting that audiospatial attention is biased toward the right hemispace (Sosa, Teder-Sälejärvi, & McCourt, 2010). This could explain the audio-tactile facilitation observed at farther distances in the right hemispace. Yet, the rightward auditory attentional bias appears to hold for both right- and left-handers (Dufour, Touzalin, & Candas, 2007), whereas motor abilities clearly differ between left- and right-handers. Therefore, examining lateral auditory peripersonal space in left-handers may help disentangle the respective contributions of attentional and motor factors to peripersonal space anisotropy. The fact that, in Hobeika et al., 2018, left-handers did not exhibit lateral asymmetry—unlike right-handers—suggests that attentional bias alone cannot account for the peripersonal space lateral anisotropy. An important methodological consideration in the present study is the use of a blocked design to present auditory stimuli from front and rear hemispaces in separate sessions. While this approach was necessary to minimize front–back confusions arising from the limitations of binaural rendering and static head position, it may have also influenced participants'

allocation of attention. Specifically, blocking by hemifield could have enhanced spatial attention toward the expected region, potentially amplifying the front–rear asymmetry observed in the data. Moreover, the fact that participants had their eyes open and were instructed to fix a cross may have induced a greater attentional focus towards the front space. Future studies could examine this attentional contribution by employing randomized presentation of front and rear stimuli combined with dynamic head tracking or explicit attentional manipulations and by comparing data obtained with eyes open and closed, to better understand how attention interacts with multisensory integration in peripersonal space.

Audio-tactile integration phenomena have been shown to depend both on the part of space in which the stimuli are located (Farnè & Làdavas, 2002; Occelli et al., 2011; Spence et al., 2017; Teraoka et al., 2024; Van der Stoep, Van der Stigchel, Nijboer, & Van der Smagt, 2015) and on the position of the hands in space (Serino et al., 2015; Tajadura-Jiménez et al., 2009). In the present study, participants' hands were placed in contact with the trunk and near the body's midline. In this configuration, the peripersonal space around the hand is indistinguishable from peripersonal space around the trunk (Serino et al., 2015) allowing us to isolate the effect of the spatial relationship between the sound and the body. Because the hand has a dual status—as both an effector and a body part that requires protection—both the appetitive and defensive roles of peri-hand peripersonal space are more likely to be engaged alternately or concurrently. Therefore, the current findings may not generalize to distance-dependent audio-tactile integration specifically around the hand. Future studies should manipulate hand position relative to the body to disentangle the potential confound between stimulus location and limb position when investigating potential lateral asymmetry of peri-hand peripersonal space. Moreover, considering that the hand and upper limb serve as central effectors in defensive behaviors, modifying their action capacities by manipulating their posture, position, or mobility would provide a way to further investigate the putative influence of motor abilities in shaping peri-trunk defensive peripersonal space.

Humans, as cephalized organisms, exhibit a distinct and intuitive frontality. Cephalization results in an anterior body part that first encounters the environment, dictating movement direction due to biomechanical constraints. The functional organization of three-dimensional space processing is intrinsically linked to the development of the head and brain. While sensory information can be received from multiple directions, the concentration of sense organs near or on the head, which leads the body as it moves forward, underscores the importance of front space for spatial cognition. Our results are aligned with this: the front/back differences in peripersonal coding coherent with forward-oriented gestures abilities provides further evidence that front space is not only central to sensory processing but also critical for the prioritization of behavioral responses to environmental stimuli.

5. Conclusion

Given that peripersonal space mediates animals' interactions with the external world (Serino, 2019), a deeper understanding of its processing could improve our comprehension of animals' behaviors within their environments. Our study demonstrates that human auditory defensive peripersonal space is not homogeneous around the body. Behavioral responses to approaching objects vary depending on their position along the front/rear and left/right axes of the perceiver's body. Considering the influence of gravity, the up/down axis is also likely significant in assessing the relevance of external events for the organism (Bufachi & Iannetti, 2016). Along with the investigation of the emotional, attentional and motor determinants of the observed anisotropy, future research should examine audio-tactile integration in depth with sounds approaching from above or below to further develop a tridimensional model of peripersonal space coding. While it remains to be determined whether the results we observed in a laboratory setting predicts those in more complex environments, such a 3D peripersonal space model would provide useful insights for exploring the benefits of audio-tactile signals in more applied settings and would have potential implications for refining human–system interfaces design.

CRediT authorship contribution statement

Augustin Amiel: Investigation, Software, Formal analysis, Writing – original draft, Writing – Review & Editing. **Lise Hobeika:** Conceptualization, Methodology, Writing – Review & Editing. **Isabelle Viaud-Delmon:** Conceptualization, Methodology, Writing – Review & Editing. **Marine Taffou:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – Review & Editing, Supervision, Funding acquisition.

Ethics

The conditions of our ethics approval do not permit public archiving of anonymised study data. Readers seeking access to the data should contact the corresponding author Marine Taffou. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data and contingent upon the establishment of a formal data sharing agreement.

Declaration of competing interest and ethics

We have no conflicts of interest to disclose.

The study was conducted in accordance with the Declaration of Helsinki, and approved by the French Ethic Committee (CPP Nord-Ouest I - CPP n°2019-A01131-56).

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Scientific transparency statement

DATA: No raw or processed data supporting this research are publicly available.
CODE: All analysis code supporting this research is publicly available: https://link.springer.com/content/pdf/10.3758/BF03193160.pdf.
MATERIALS: No study materials supporting this research are publicly available.
DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.
PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.
For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.11.015.

Appendix

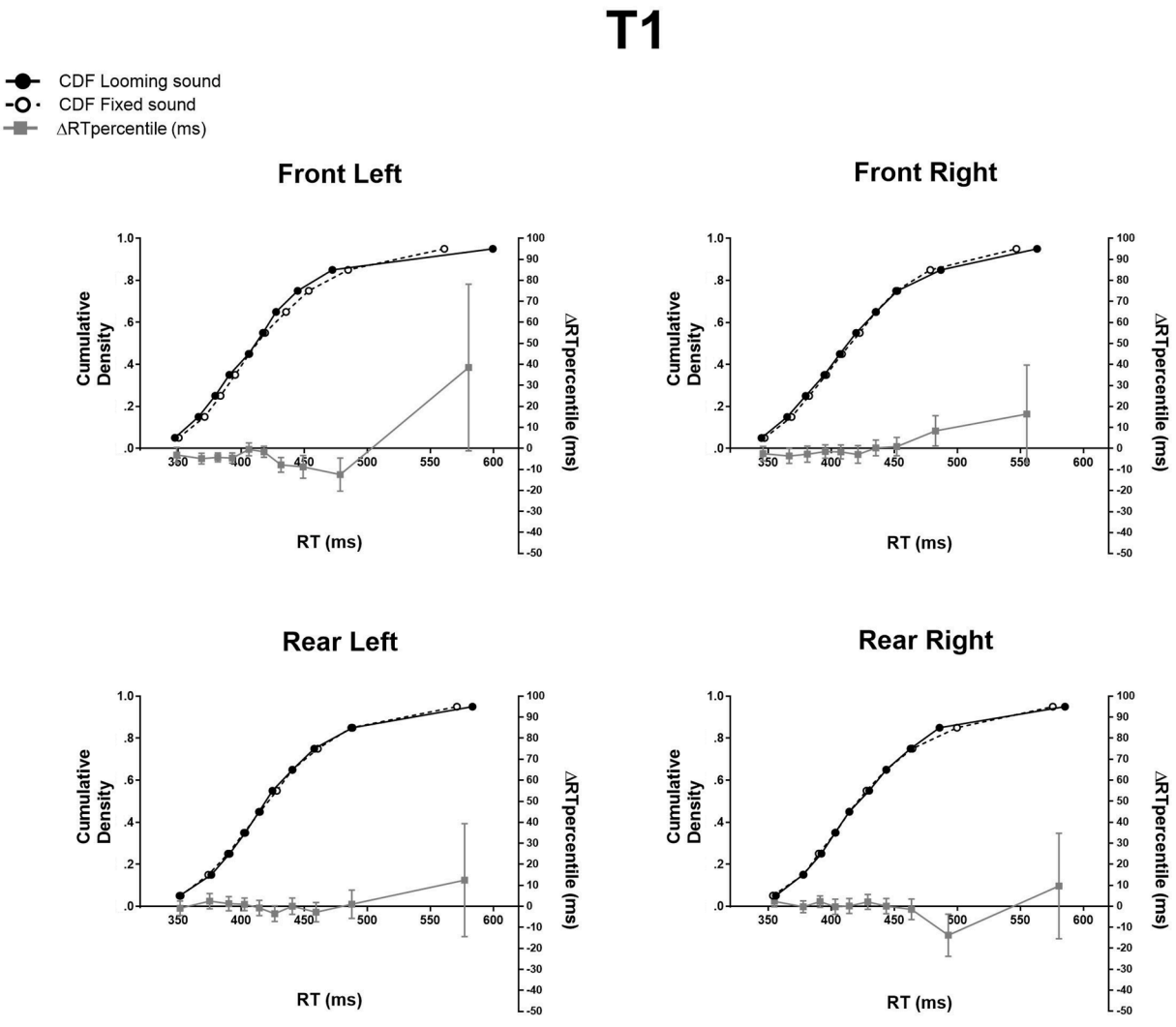

Fig. A.1 – Audio-tactile interaction experiment results - Analysis of reaction times (RTs) distribution for the T1 delay condition. This figure depicts the average cumulative density function (CDF) of RTs for participants (n = 34) at delays T1 in the front (top panels) and rear (bottom panels) hemifields in the left (left panels) and right (right panels) hemispaces under looming (black circles) and fixed (white circles) sound conditions. To ease the visual assessment of the horizontal separation of the two CDFs, the mean difference in RT percentile values between looming and fixed sound conditions (ΔRTpercentile ± SEM) is also displayed (grey squares). At delay T1, no significant difference is observed in RTs distribution between looming and fixed sound conditions for neither of the front left, front right, rear left and rear right part of space.

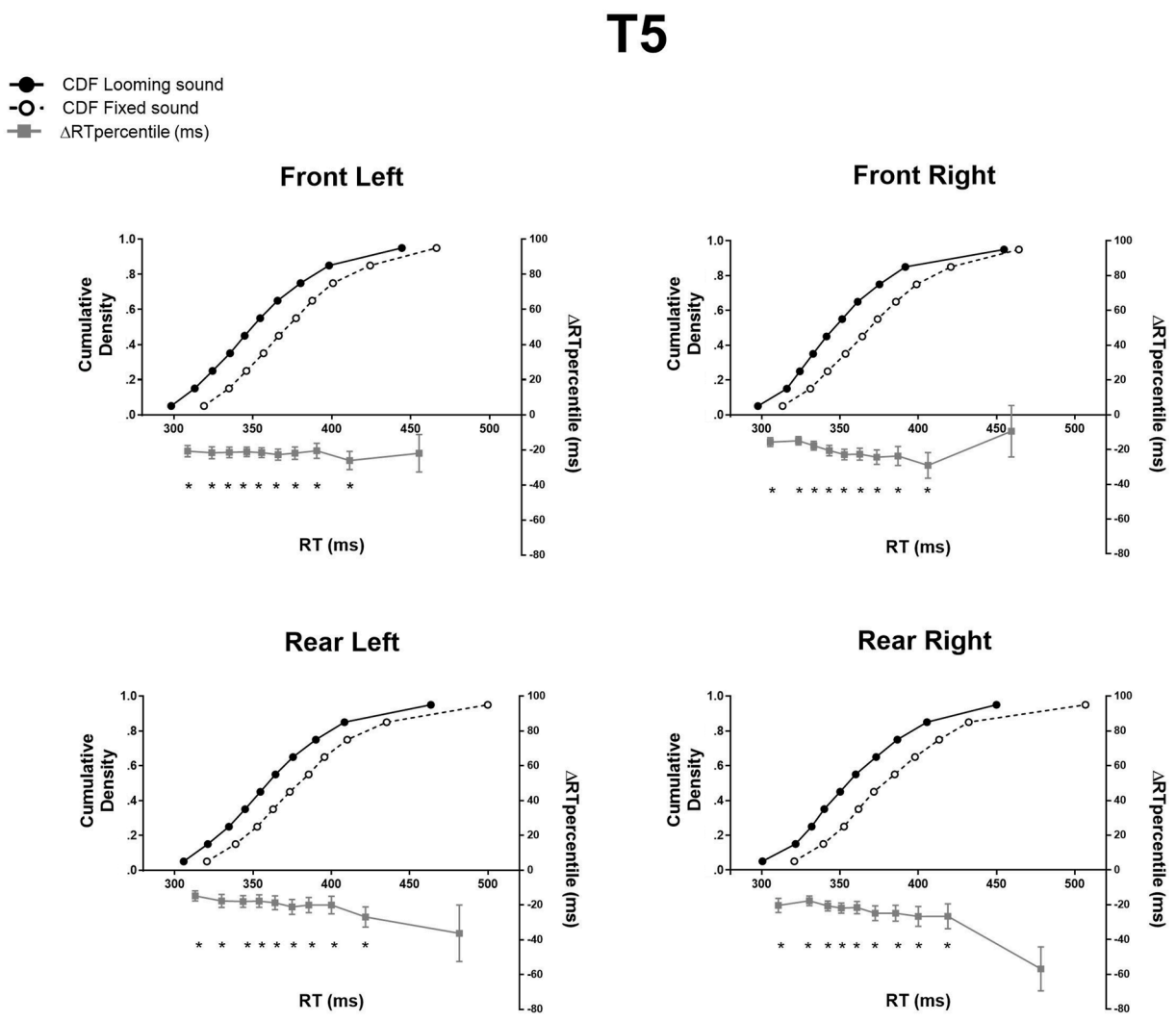

Fig. A.2 – Audio-tactile interaction experiment results - Analysis of reaction times (RTs) distribution for the T5 delay condition. This figure depicts the average cumulative density function (CDF) of RTs for participants (n = 34) at delays T5 in the front (top panels) and rear (bottom panels) hemifields in the left (left panels) and right (right panels) hemispaces under looming (black circles) and fixed (white circles) sound conditions. To ease the visual assessment of the horizontal separation of the two CDFs, the mean difference in RT percentile values between looming and fixed sound conditions (ΔRTpercentile ± SEM) is also displayed (grey squares). At delay T5 and four each of the four part of space the sound source can be located, participants' RTs are generally faster in the looming compared to the fixed sound condition. Significant differences are indicated with an asterisk (*).

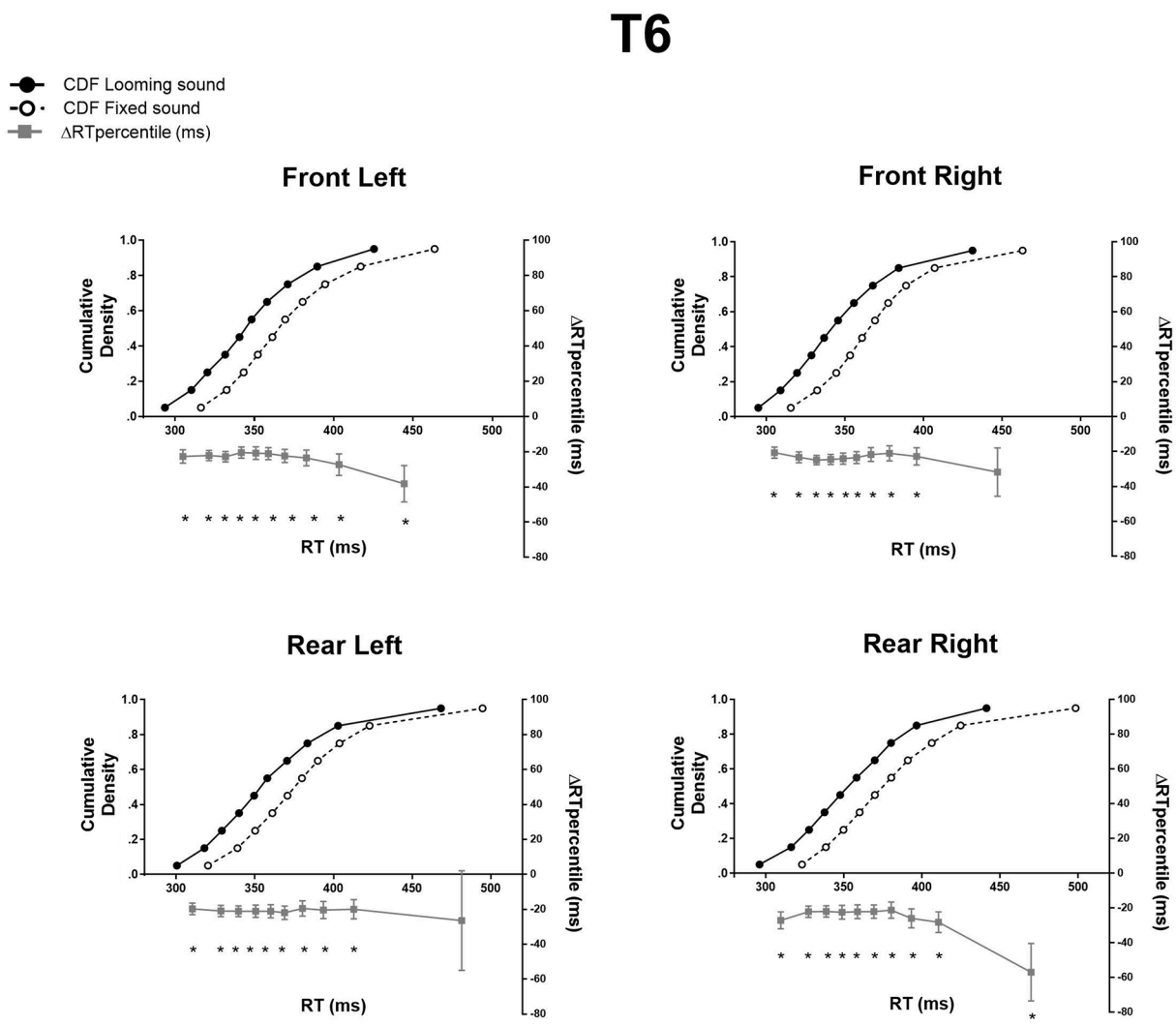

Figure A.3 – Audio-tactile interaction experiment results - Analysis of reaction times (RTs) distribution for the T6 delay condition. This figure depicts the average cumulative density function (CDF) of RTs for participants (n = 34) at delays T6 in the front (top panels) and rear (bottom panels) hemifields in the left (left panels) and right (right panels) hemispaces under looming (black circles) and fixed (white circles) sound conditions. To ease the visual assessment of the horizontal separation of the two CDFs, the mean difference in RT percentile values between looming and fixed sound conditions (ΔRTpercentile ± SEM) is also displayed (grey squares). At delay T6 and four each of the four part of space the sound source can be located, participants' RTs are generally faster in the looming compared to the fixed sound condition. Significant differences are indicated with an asterisk (*).

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