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THE IMPACT OF LOOMING SOUND DURATION ON PERIPERSONAL SPACE MEASUREMENT

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ABSTRACT

Peripersonal space (PPS) has been described as a subjective region immediately surrounding the body. Distinct neurological and behavioral patterns are found when stimuli originate in this region. In what is arguably the most common task to measure PPS, a looming cue in one sensory modality (e.g., auditory) is followed by a tactile cue. Participants are requested to react to the latter. Quicker reaction times are thought to be linked to the sound originating within PPS. Given that PPS is dynamic and changes according to subjective states, this task is crucial for experimental work in body and spatial perception. Here, we compare the suitability of 3 s and 2 s looming pink-noise stimuli for measuring PPS, aiming to reduce experiment duration without compromising accuracy and to streamline experimental protocols. The stimuli were designed to simulate a sound source approaching laterally from the right towards the listener's head. 13 participants underwent two PPS tasks (3 s and 2 s looming sounds respectively) in a counterbalanced manner to assess the accuracy of each and whether differences between PPS and far space occur for both sounds. Our findings contribute to the methodological refinement of future PPS research and the wider applicability of the task.

Keywords: *multisensory body perception, peripersonal space, multisensory integration, auditory sources, looming sounds).*

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1. INTRODUCTION

The perception of one's body is elemental to our interaction with the world and others [1, 2]. Being aware of the space immediately surrounding oneself is of particular importance. This region is within the reach of one's actions, allowing us to interact with objects, and avoid potential threats. It has been called peripersonal space (PPS), a term originally introduced by Rizzolatti and colleagues [3, 4] after observing a group of neurons in macaque monkeys that activated when auditory or visual stimuli were presented near the monkey's body, but not far away from it. These peculiar neuropsychological responses in humans can be studied indirectly through behavioral assessments [5]. Arguably the most widely used procedure for this is called the PPS task [6], in which an either auditory or visual looming cue precedes a tactile stimulus [7]. Participants have to respond as soon as the touch is felt. As the looming cues appear closer to the body, responses to the tactile stimulation become more rapid. The area at which quicker reaction times are found for stimuli preceded by a looming cue compared to isolated tactile stimuli is interpreted as the PPS region. Interestingly, this area seems to vary according to transient changes in body perception. For example, it is reduced in amputees when not wearing a prosthesis but it increases when worn [8]. The PPS task is thus a powerful tool to experimentally study body perception and related spatial aspects.

Despite its relevance, there is no consensus on the parameters employed in such a task. There are versions in which the looming cue is presented visually in a headmounted display or acoustically through speakers or headphones [7, 9, 10]. Though each of these may be important for certain contexts, the audio-tactile version provides certain benefits; and, to our best of knowledge, it is the most widely used approach. This setup can be important, for example, when using this task for studying the effects of sound on body perception [11–13], so that there is no need for additional devices. Or, when visual cues are involved in the experimental manipulation, the auditory PPS task allows researchers to ensure that the resulting perceptual changes are not exclusively due to visual recalibration of space [14]. The task may be further used without occluding vision, which may be relevant when awareness of the visual surroundings is important for the experimental manipulation (ibid). However, variations in apparatus, stimulus duration, distance, speed and direction of the looming source across different studies make it difficult for researchers to determine which is most appropriate for their setting [6, 7, 15, 16].

To contribute to the systematic understanding of how different stimuli features impact the task, we performed this study comparing the use of a 2 s versus 3 s looming sound. These sounds were generated to be used on headphones. In contrast to complex speaker arrays [7, 14, 16], headphones make this task more easily usable. We simulated the auditory looming source by using virtual acoustic techniques (e.g., [17–19]). Specifically, we generated a pink noise moving source onto which directional cues were then introduced by convolving the signal with the left and right sets of head-related transfer functions (HRTFs) that correspond to the spatial direction of a moving source approaching rightwards laterally along a straight trajectory toward the participant's head [see section 3.1]. Most previous studies have relied exclusively on amplitude to provide the sensation of a sound source approaching, and have simulated sources moving along the front-back axis [6, 7, 14, 16]. However, we used HRTFs to enhance spatial cues and chose to simulate a sound source approaching laterally [20], as human auditory localization is more accurate along the left–right than the front–back axis (see [21] for a review). There are examples of other studies [9, 10] that also employed HRTFs, with only [10] employing Laterally approaching sound source. In that study, a 4 s sound was used, consisting of a 2 s moving source period between two 1 s static source location periods. The chosen 2 s duration is, to our knowledge, the shortest used for this task to date. Although the duration of the looming sound varies widely across studies, other studies have used durations over 2 s, ranging from 2.5 s [14], 2.75 s [16], and 3 s [6, 23]; and up to 8 s [7]. However, it remains unclear whether effects related to PPS differ depending on the duration of the sound used. This is precisely what we aim to investigate in the current study. Additionally, we seek to explore ways to shorten the task— both in terms of stimulus duration and the overall experiment length—to reduce participant fatigue. This would also help make the task more suitable for measuring transient effects, such as those induced by bodily illusions impacting PPS [14, 24, 25].

If the task can be shortened to 2 s whilst yielding similar results to the more common 3 s version, experiments can become significantly shortened and thus more accessible. Furthermore, if a different region of PPS is found according to the duration of the looming sound, this can impact our understanding of PPS since it might signify that the task is already providing a prominent amount of noise. Though this is a preliminary study to systematically understand how different acoustic attributes might impact the PPS task, it may yield important information for future research directions.

2. METHODS

2.1 Participants

13 participants (4 female, 9 male, mean age 33 years, range: 29-44) took part in the study. Two were left-handed and the remaining 11 were right-handed. All were university students or faculty members and reported having normal hearing and touch. The study was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by the Research Ethics Committee of the Universidad Carlos III de Madrid. Informed consent was obtained. All participants took part in both experiments.

2.2 Procedure and experimental preparation

Participants sat in front of a monitor with a table positioned on their right side. Their right arm was comfortably stretched onto the table, with a molded silicone pad (15 x 15 x 1cm) placed under the palm from which tactile stimulation was provided. A response button was placed within easy reach of the left hand.

Initially, participants underwent a demonstration of the tactile stimulation, during which they were instructed to press the button as soon as the vibration was felt. Following this practice, instructions were provided regarding the main experimental task. Participants were instructed to maintain visual fixation on a central cross displayed on the monitor and to refrain from moving their head laterally during the experimental procedure. They then proceeded to perform 5 practice trials. The two experiments followed.

2.3 Experimental Design

The two experiments had the same structure, consisting of the PPS task followed by a questionnaire (see Tab. 1). Two scheduled breaks were included within each experiment.

The PPS task consisted of two conditions: either tactile stimulation only (Baseline condition), or audio-tactile stimulation with the looming sound preceding the touch

(Audio-Tactile condition). The onset for each trial was 1000 ms after the appearance of a fixation cross on the screen. Participants pressed a button as soon as the tactile stimulation was felt. For the audio-tactile trials, the looming sound was presented on the onset. The tactile stimuli were delivered at seven distinct temporal delays from the onset. These delays were equally spaced across the sound duration (i.e., for the 2-second experiment at 250, 500, 750, 1000, 1250, 1500, and 1750 ms; and for the 3-second experiment at 375, 750, 1125, 1500, 1875, 2250, and 2625 ms from the onset). 16 repetitions were presented for each delay and condition yielding a total of 224 trials (112 per condition). Additionally, 21 catch trials consisting exclusively of auditory stimuli, in which participants were instructed not to response [10], were interspersed, resulting in 245 trials per block.

The questionnaire followed the PPS task and assessed experiential qualities of the audio-tactile stimulation (Tab. 1). Participants were repeatedly presented with the sounds and answered the items on Likert-scale. An exception was the distance estimation item, where the initial and final location of the looming sound was estimated by experimenter standing where there participants pointing to where they believe the sound location is, and measuring the distance to the participant. Upon completion, participants proceeded to the PPS task and questionnaire for the following experiment. The order of the experiments was semi-counterbalanced so that 7 participants experienced the 2-seconds experiment first and 6 participants the 3-seconds experiment first.

2.4 Apparatus and stimuli synthesis

Auditory stimuli were synthesized to simulate the movement of pink noise from the right toward the listener in stereo. This was achieved using a head-related transfer function (HRTF) implemented in MATLAB (MathWorks, Natick, MA, USA), following the code and method described in [10]. Two stimulus durations were generated: one lasting 2 s and the other 3 s. The sound movement speed was kept constant at 50 cm/s as in [10]. For the 2 s stimulus, the simulated sound source initiated at 100 cm as in [10], whereas for the 3 s stimulus, the starting distance was 150 cm. This 150 cm distance was chosen to achieve a 3 s duration while keeping the speed at a constant 50 cm/s between the sounds. The stimuli incorporated a propagation and attenuation factor consistent with room-temperature air, and no additional reverberations were included [10]. The auditory stimuli were delivered through closed-back headphones (Sennheiser HDA 300), with high passive ambient noise attenuation (>30 dBA) which was essential to help isolate vibration and button click sounds).

The tactile stimuli were synthesized to ensure precise temporal delivery during audio-tactile trials. An 80 Hz sawtooth tone lasting 200 ms [10] was generated in Audacity and delivered through an audio-driven haptic actuator placed on a rectangular molded silicone pad (10 x 10 x 1cm). The signal was played from a separate audio channel, on a track matching the duration of the auditory stimuli (i.e., either 2 or 3 s) for the corresponding experiment to ensure precise timing. The tactile signal started at each of seven equidistant time points relative to the start of the looming sound. For the 2-second experiment, this was at 250, 500, 750, 1000, 1250, 1500, and 1750 ms; for the 3-second experiment, at 375, 750, 1125, 1500, 1875, 2250, and 2625 ms from the start of the audio track. Consequently, seven distinct tactile tracks were produced for each experiment. During audio-tactile trials, the corresponding tactile track was played simultaneously with the auditory track.

Stimulus presentation was controlled using PsychToolBox [22], running on a Windows laptop. A digital-to-analog converter interfaced via WASAPI drivers ensured precise, synchronized delivery of both auditory and tactile stimuli. A 21-inch HD monitor displayed a fixation cross. Participants responded using a designated button (Cherry MX Blue, Cherry GmbH, Germany), and all equipment was arranged on a table configured to support a comfortable posture for the participant throughout the trial.

2.5 Data Processing

Reaction times (RTs) were calculated as the interval between the trial onset (1000 ms after the appearance of the fixation cross) and the participant's keypress, adjusted for the timing of the tactile stimulus onset. Trials in which the RT was negative (i.e., responses occurring before stimulus onset), or those in which multiple keypresses were recorded were excluded from further analysis. Following [10], for each of the experiments (2-second and 3-second), mean RTs to tactile targets were calculated for every distance (i.e., temporal delay), separately for the Baseline and Audio-Tactile conditions. RTs exceeding 2.5 standard deviations from the mean RT for the corresponding distance and condition were considered outliers and trimmed from the analyses (fewer than 10% removed for each subject).

Mean RTs at the different temporal delays for each condition were fitted to a sigmoidal function as described in [6] using six temporal delays obtained by pairwise averaging of adjacent temporal delays. This procedure was implemented to reduce variability of each observed point in the curve [23]. 3 participants in the 2-second experiment and 4 participants in the 3-second experiment were excluded from the analyses of the PPS task because their Baseline or Audio-Tactile data did not fit the sigmoidal function (R2 < 0.1).

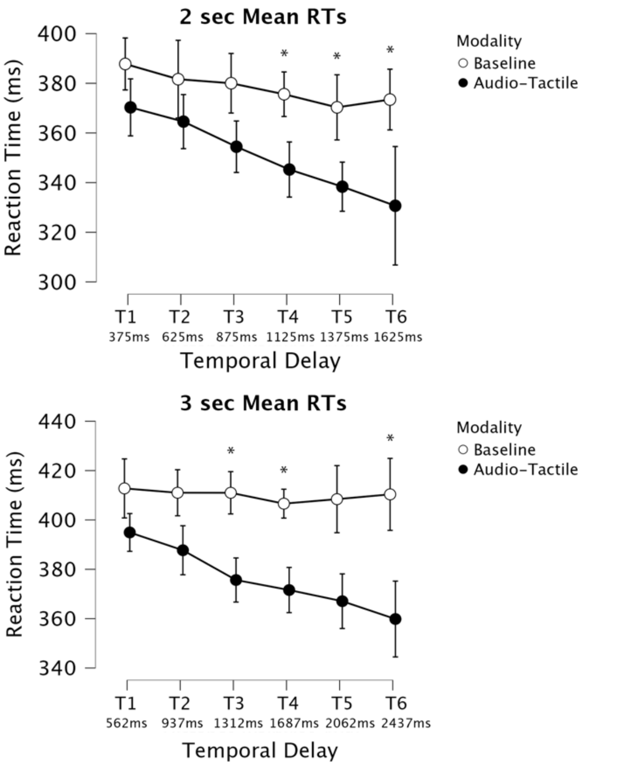

Figure 1. Group-average tactile RTs. Results are presented separately for the 2-second (N = 10, *top*) and 3-second (N = 9, *bottom*) experiments. Error bars represent 95% confidence intervals from withinsubject variance. Stars (*) represent a significant difference at group level (p < 0.05, Bonferronicorrected).

Repeated-measures Analysis of Variance (ANOVAs) were performed on the RT data from the PPS task of each experiment, with the within-subject factors of Modality (Baseline, Audio-Tactile) and Temporal Delay (T1, T2, T3, T4, T5, T6). Based on statistically significant effects identified in the repeated-measures ANOVA, we conducted follow-up analyses using paired-samples t-tests, applying Bonferroni correction for multiple comparisons. To further support and complement these frequency-based analyses, Bayesian paired-samples t-tests (Wilcoxon signed-rank tests, implemented in JASP with Cauchy's probability distribution centered at 0 and width 0.707) were performed. Bayes Factors (BFs) were computed to quantify evidence in favor of either the alternative hypothesis (i.e., significant differences between experimental conditions) or the null hypothesis (i.e., no difference between conditions). We adopted the interpretation criteria from [26], considering a BF > 10 as strong evidence, a BF of 3–10 as moderate evidence for the alternative hypothesis, a BF of 0.10–0.33 as moderate evidence, and a BF < 0.10 as strong evidence supporting the null hypothesis [10].

Following [10], the boundary of the audio-tactile PPS was determined by identifying the farthest interval at which both Bonferroni-corrected paired-samples t-tests and corresponding Bayesian analyses revealed statistically significant facilitation of tactile RTs compared to unimodal baseline RTs, consistent with prior methodologies.

Additionally, we performed sigmoid curve fitting on the mean RTs of all included participants for the Baseline and Audio-Tactile conditions. The sigmoid fitting provided estimates of the central point (xc), reflecting the boundary of the PPS representation, and the slope (k), indicating the sharpness of the transition from far to near space. Following the established methodology [6, 23, 27], we compared the xc and k parameters between Baseline and Audio- Tactile conditions to further assess the extent and characteristics of PPS boundaries. Differences in the questionnaires between the 2-second and 3-second experiments were analyzed using a Bayesian t-test.

3. RESULTS

3.1 Peripersonal space task

In the 2-second experiment, involving the 2-second sound, repeated-measures ANOVA revealed a main effect of Modality, $F(1, 8) = 9.55$, $p = .015$, $\eta^2 = .35$, indicating that the type of sensory input had a strong influence on participants' RTs. There was also a main effect of Temporal Delay, $F(1.91, 15.27) = 21.35$, $p < .001$ (Greenhouse-Geisser corrected), $\eta^2 = .18$, suggesting that RTs varied across distance levels. Importantly, the two-way interaction showed a significant interaction of Modality and Temporal Delay ($F(2.30, 18.43) = 3.83$, $p = .036$ (Greenhouse-Geisser corrected), $\eta^2 = .04$) indicating that the influence of Temporal Delay on RTs depended on the Modality.

Similarly, in the 3-second experiment, the analysis revealed a main effect of Modality, $F(1, 9) = 25.779$, $p < .001$, $\eta^2 = .522$, a significant main effect of Temporal Delay, $F(3.21, 61.14) = 7.236$, $p = .005$ (Greenhouse-Geisser corrected), $\eta^2 = .080$, and a significant interaction of

Modality and Temporal Delay, $F(3.03, 57.65) = 7.519$, $p = .002$ (Greenhouse-Geisser corrected), $\eta^2 = .053$.

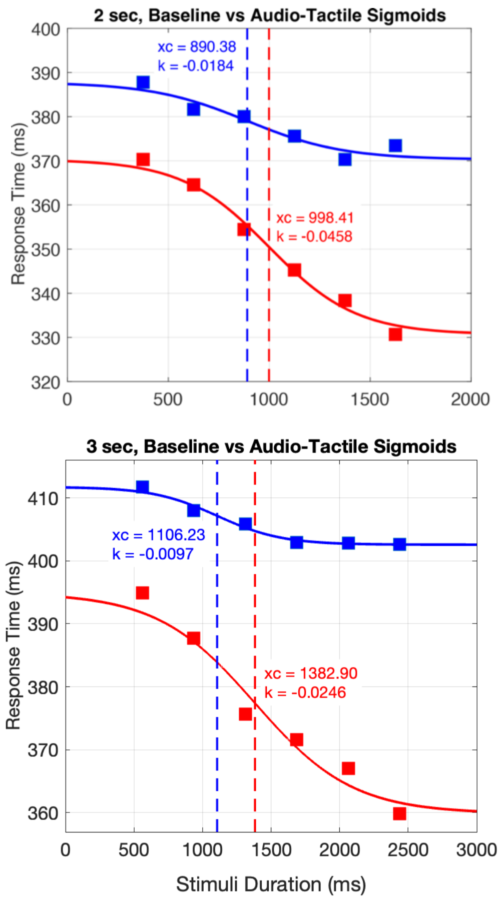

Figure 2. Sigmoidal functions describing the relationship between RTs and sound distance in the Audio-Tactile condition (red) and the Baseline condition (blue). Results are presented separately for the 2-seconds experiment (*top*; N=10) and the 3-seconds experiment (*bottom*, N=9). The dashed vertical lines represent the central point of the sigmoid.

The relationship between RTs and the different temporal delays at which the tactile stimulus was administered (1 to 6) is represented in Fig. 1 for the Baseline and Audio-Tactile conditions.

Bayesian Wilcoxon Signed-Rank Test for the 2-second experiment showed significant facilitation of Audio-Tactile RTs compared to Baseline, beginning with strong evidence at T4 (Wilcoxon Bonferroni-corrected: $p = .008$; $BF_{10} = 22.49$), continuing at T5 (Wilcoxon: $p = .008$, $BF_{10} = 27.00$), and becoming very strong at T6 (Wilcoxon: $p = .004$, $BF_{10} = 56.03$). For the 3-second experiment, significant facilitation began at T3 (Wilcoxon Bonferronicorrected: $p = .002$, $BF_{10} = 64.49$), continued at T4 (Wilcoxon Bonferroni-corrected: $p = .002$; $BF_{10} = 64.90$), slightly decreased to strong evidence at T5 ($p = .006$, borderline strong; $BF_{10} = 25.64$), and returned to very strong at T6 ($p = .002$; $BF_{10} = 82.00$). Based on these results, we estimate the PPS boundary for the 2-second sound to be between T3 and T4 (875ms and 1125ms), and for the 3-second sound to be between T2 and T3 (937.5ms and 1312.5ms).

To further investigate the differential effects of the two sounds on tactile processing, we compared the parameters derived from sigmoid curve fitting (central point xc and slope k) for Baseline and Audio-Tactile conditions separately for each experiment (see Fig. 2). For the 2-second experiment, the xc (central point) is 890.38 ms in the Baseline condition and 998.41 ms in the Audio-Tactile condition. The k (slope) became steeper, changing from -0.0184 (Baseline) to -0.0458 (Audio-Tactile). Similarly, in the 3-second experiment, the xc is 1106.23 ms in the Baseline and 1382.90 ms in the Audio-Tactile condition. Moreover, k again increased in steepness, from -0.0097 (Baseline) to -0.0246 (Audio-Tactile), indicating a sharper transition from far to near space in the Audio-Tactile condition.

3.2 Questionnaires

As shown in Tab. 1, in both the Audio-Tactile conditions of the 2-second and 3-second experiments, participants reported similar mild perceptions of approach, urgency, or speed.

Regarding the estimated sound location (items 10 and 12, Tab. 1), for the 2-second experiment, the average estimated start is ~153.6 cm (above the HRTF simulated 100 cm), ending at ~12 cm behind or past them (a negative value). For the 3-second experiment, participants estimated the location of the sound (items 10 and 12) starting at ~189 cm (close to the actual HRTF-simulated 150 cm yet still slightly overestimated) and ending at ~3.6 cm (very close to actual 0 cm simulated). Though there are no significant differences according to the statistical analyses, participants were more accurate in their estimation for the 3-second experiment.

Furthermore, nonparametric Wilcoxon tests comparing responses between the Audio-Tactile conditions of the 2-

second and 3-second experiments revealed no significant differences. All p-values from the Wilcoxon signed-rank tests exceeded .05, indicating no statistically significant differences for any of the questionnaire items when comparing 2-second and 3-second experiments. This suggests that the 2 s and 3 s dynamic sounds elicited comparable subjective and spatial perceptions. However, readers should consider these findings inconclusive due to the small sample size for the questionnaire.

Table 1. Questionnaire items, response scales, and results for the 2-second and 3-second Audio-Tactile conditions. Median and interquartile range (IQR) for each item in both conditions are indicated, along with the p-values from Wilcoxon signed-rank tests comparing responses between the two experiments.

Question	Scale	3s Median	3s IQR	2s Median	2s IQR	p
1. "I felt that the sound was approaching towards me."	-3 to +3	2	1	2	0	0.773
2. "I felt a sense of urgency or threat from the sound."	-3 to +3	1	2	1	3	0.784
3. "I felt the sound was too fast for me to react to."	-3 to +3	-2	1	-1	2	0.234
4. "I could feel the vibration on my hand very clearly."	-3 to +3	3	0	3	0	NA
5. "I felt I was completely focused on the task."	-3 to +3	1	1	2	1	0.12
6. "I felt that the speed of the sound approaching was:"	1 to 7	5	1	5	0	0.34
7. "As I was hearing the sound, I felt (SAM Pleasure)."	-4 to +4	0	1	-1	1	0.624
8. "As I was hearing the sound, I felt (SAM Arousal)."	-4 to +4	1	3	1	3	0.944
9. "As I was hearing the sound, I felt (SAM Dominance)."	-4 to +4	-1	0	0	1	0.197
10. "Estimated starting distance of the sound" (cm)	— (cm)	150	189	150	152	0.197
11. "How certain are you of your estimation?"	0 to 100	80	20	80	20	0.587
12. "Estimated ending distance of the sound" (cm)	— (cm)	0	8	0	14	0.108
13. "How certain are you of your estimation?"	0 to 100	80	20	80	15	1

4. DISCUSSION

Our study suggests that both the 2-second and 3-second experiments can assess the PPS region according to differences in tactile RTs between the Baseline and Audio-Tactile conditions. This implies that the 2 s looming sound could be used as a shorter alternative in the audio-tactile PPS task. To our knowledge, this is the first time that such a short looming sound has been used, which could imply a significant reduction in the duration of future experiments.

Interestingly, in our study the temporal delay at which the PPS region was found does not coincide between experiments (roughly between 875 and 1125 ms for the 2-second experiment, and between 937.5 and 1312.5 ms for the 3-second experiment). Although there is a coincidental period in that range, the 2-second and 3-second looming stimuli respectively implied a different initial distance (100 cm for the former and 150 cm for the latter). Therefore the similar timing does not correspond to an equivalent distance. Previous research has relied on time to infer the spatial location at which peripersonal space is found, and our study suggests that, depending on the type of stimulation used, even though timings are similar, the spatial location differs. This interpretation could have significant implications in how previous studies that infer physical distance for PPS based on the timing of the sound are understood. For example, rather than spatial accuracy, the looming sound might simply strengthen the prediction that a tactile cue will arrive, yielding faster reaction times but not necessarily describing an accurate spatial region. In our study this interpretation could explain why for both experiments the difference is found around 1 s after the onset but with differences in physical area. It should be noted that distance accuracy is not particularly acute in humans [28] and despite the practicality of involving headphones and generic HRTFs, speaker arrays might provide more accurate spatial cues. In fact, in our study participants estimated both sounds to appear at a similar distance despite the differing simulated starting locations (100 and 150 cm, mean estimation 153.6 and 189 cm respectively).

Further, looming sounds in PPS studies have been presented at substantially different speeds, from as low as 22 cm/s [7] to as high as 210 cm/s [9]. While the present work focuses on the effect of sound duration as a function of distance, future studies could explicitly manipulate speed to investigate how different approach velocities modulate PPS representation. In this experiment, we recorded a very small sample and further data collection would be important for more conclusive findings. Still, our statistical results are clear, and our Bayesian evidence is substantial for the PPS task. Future studies could involve larger samples and ideally a staircase procedure (see e.g., [9]) to optimize the approach and find more exact quantities at which the individual's peripersonal space is found.

For the questionnaire data, no clear evidence were found at large for differences or a lack thereof. Both experiments yielded similarly mild responses in respect to feelings of approach, urgency, and speed. However, particularly for these questionnaire findings—which lack trial repetitions—they should be considered with caution due to the small sample. However, cautiously, participants' estimated distances of the initial and final locations of the looming sounds are worth highlighting. For the 2-second experiment, participants' estimate (~153.6 cm start, ~-12 cm end) was quite far from the theoretical simulated location (100 cm start, 0 cm end), while for the 3-second experiment, participants' estimated location (~189 cm start,

~3.6 cm end) was closer to the simulated one (150 and 0 cm respectively). The reasons for this increased accuracy for the longer sound are unclear, but perhaps a longer stimulus implies more time for spatial processing.

It should be noted that the 2-second looming sound appeared to result in a steeper slope of the sigmoidal function (i.e., a larger absolute value of the slope parameter k) than the 3-second sound (although these conditions were not directly compared). This steeper slope is often interpreted as an indicator of greater sensitivity in PPS representation, reflecting a more distinct and abrupt transition between "non-PPS" and "PPS" zones [5]. In contrast, the shallower slope observed with the 3-second sound suggests a more gradual integration of space, where the shift from far to near space unfolds more progressively. This may reflect reduced spatial sensitivity or increased uncertainty about stimulus proximity. Notably, such a pattern has been observed in studies involving altered bodily states—such as during experimentally-induced body transformation experiences—where the PPS boundary becomes more diffuse, potentially due to changes in sensorimotor expectations or embodiment. Therefore, while the 2-second sound may afford more precise spatial encoding, the more gradual slope associated with the 3-second sound could also offer valuable insight into the flexibility of PPS representation under varying perceptual conditions. Our findings indicate that both durations are effective, however the 2-second stimulus may better capture earlier PPS responses and reduce trial time (potentially important for fatigue-sensitive settings or clinical populations), but the 3-second stimulus might provide more spatial cues and more precise spatial encoding which could be important for specific settings and a future avenue of research.

This study is an initial step in attempting to systematically investigate which attributes of looming sounds may impact the PPS task. Although preliminary, our findings provide routes for future research in this direction that might help optimize this important task for the study of body perception and body transformation experiences.

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