# Multisensory peripersonal space:

# Visual looming stimuli induce stronger response facilitation to tactile than auditory and visual stimulations

Geers, L., Kozieja, P. & Coello, Y.

**Affiliation**

Univ. Lille, CNRS, UMR 9193 - SCALab - Sciences Cognitives et Sciences Affectives, F-59000 Lille, France

**Corresponding author**

Pr. Yann Coello

UMR CNRS 9193 SCALab

University of Lille

BP 60149

59653 Villeneuve d'Ascq cedex, France

*Tel: +33 320416446 / Fax*: *+33 320416032*

Email: *yann.coello@univ-lille.fr*

**Declaration of interest**

The authors declare no competing interests.

**Abstract**

Anticipating physical contact with objects in the environment is a key component of efficient motor performance. Peripersonal neurons are thought to play a determinant role in these predictions by enhancing responses to touch when combined with visual stimuli in peripersonal space (PPS). However, recent research challenges the idea that this visuo-tactile integration contributing to the prediction of tactile events occurs strictly in PPS. We hypothesised that enhanced sensory sensitivity in a multisensory context involves not only contact anticipation but also heightened attention towards near-body visual stimuli. To test this hypothesis, Experiment 1 required participants to respond promptly to tactile (probing contact anticipation) and auditory (probing enhanced attention) stimulations presented at different moments of the trajectory of a (social and non-social) looming visual stimulus. Reduction in reaction time as compared to a unisensory baseline was observed from an egocentric distance of around 2 m (inside and outside PPS) for all multisensory conditions and types of visual stimuli. Experiment 2 tested whether these facilitation effects still occur in the absence of a multisensory context, i.e., in a visuo-visual condition. Overall, facilitation effects induced by the looming visual stimulus were comparable in the three sensory modalities outside PPS but were more pronounced for the tactile modality inside PPS (84 cm from the body as estimated by a reachability judgement task). Considered together, the results suggest that facilitation effects induced by visual looming stimuli in multimodal sensory processing rely on the combination of attentional factors and contact anticipation depending on their distance from the body.



**Keywords:** Multisensory Integration; Arousal, Object-Directed Motor Action; Social Perception

## Introduction

The ability to predict the sensorimotor consequences of interactions with objects located in our reachable space, commonly referred to as peripersonal space (PPS), is crucial for precise and adaptable movements (Di Pellegrino & Làdavas, 2015; Wolpert & Flanagan, 2001). These predictions not only facilitate motor adjustments when actual sensory feedback does not match these predictions (Johansson & Westling, 1988; Pickering & Clark, 2014; Wolpert et al., 2001) but also enable the anticipation of potential collisions with nearby objects (Cléry et al., 2017). Given that objects in close proximity can represent targets or threats to the body, the ability to predict their sensorimotor consequences thus plays a critical role in both voluntary motor control and defensive behaviour (Brozzoli et al., 2011; de Vignemont & Iannetti, 2015; Graziano & Cooke, 2006). In a broader sense, these predictions enable us to react quickly and appropriately to incentive or challenging objects in our environment.

A number of studies have highlighted the role of the peripersonal neurons in predicting the sensorimotor consequences of interactions with objects in our PPS (Cléry et al., 2015, 2017; Dijkerman & Medendorp, 2021; Serino, 2019). These neurons, identified through single-cell recordings in non-human primates, were shown to respond to visual or auditory stimuli when located in near-reachable PPS, but not when located in far-unreachable extrapersonal space (Colby et al., 1993; Fogassi et al., 1999; Rizzolatti et al., 1981). In addition, peripersonal neurons were shown to respond to tactile stimulation, with the specificity that their activation by visual or auditory stimuli enhances their response to tactile stimulation (Avillac et al., 2007; Rizzolatti et al., 1981). Hence, these neurons would contribute to a specific multisensory representation of PPS. In line with the idea that this multisensory representation allows for the anticipation of physical contact with the body in the context of both goal-directed and defensive motor behaviour, peripersonal neurons were found to be part of a frontoparietal network encompassing areas around the intraparietal sulcus (Colby et al., 1993; Grefkes & Fink, 2005)

and the ventral premotor cortex (Fogassi et al., 1999; Rizzolatti et al., 2002) known to be involved in numerous sensory-motor functions, including the anticipation of impacts on the body (Cléry et al., 2017; Rizzolatti et al., 2002). As further support, the electrical stimulation of peripersonal neurons in monkeys has been shown to elicit defensive-like arm movements such as arm withdrawal or blocking gestures (Cooke et al., 2003; Cooke & Graziano, 2004; Graziano et al., 2005). There is thus compelling evidence, at least in non-human primates, that the presence of an object in PPS activates the peripersonal neurons, allowing for the anticipation of its sensorimotor consequences enabling in turn the facilitation of an appropriate reaction, either in terms of approach when facing incentive objects or in terms of avoidance when facing threatening objects (Cléry et al., 2017; Dijkerman & Medendorp, 2021; A. Serino, 2019). It is important to note that the functional role of PPS-related multisensory neurons implies their inherent visuo-tactile or auditory-tactile nature, as the sensory consequences of a nearby stimulus are predicted in terms of its impact on the body, thus in the tactile modality (Cléry et al., 2017).



Neuroimaging and neurostimulation studies have provided evidence for the existence of peripersonal neurons with similar multisensory properties in the human brain (Bernasconi et al., 2018; Serino et al., 2011). However, most of the evidence for the multisensory properties of the human PPS comes from one behavioural paradigm directly inspired by the single-cell studies in the monkey. This paradigm consists of a tactile detection task where tactile stimulation is provided at various moments of the trajectory of a visual (or auditory) stimulus looming towards the body. Reaction times (RTs) to tactile stimulation typically decrease with the spatial proximity of the visual (or auditory) stimulus (e.g., Canzoneri et al., 2012; Serino et al., 2015). These facilitation effects mimic those observed in the monkey and are therefore attributed to contact anticipation mechanisms subserved by the multisensory properties of the peripersonal neurons (Cléry et al., 2017; Dijkerman & Medendorp, 2021; Serino, 2019). For

this reason, the farthest distance from which the visual (or auditory) stimulus facilitates the RTs to tactile stimulation, as compared to a control condition where the tactile stimulation is provided alone or in co-occurrence with a static far stimulus, is typically considered as an indicator of the extent of the PPS-related multisensory integration processes and therefore PPS itself (*e.g.*, Amemiya et al., 2019; Noel et al., 2015; Serino et al., 2015; Stone et al., 2018).

However, accumulated evidence from behavioural studies has cast some doubt on the strict correspondence between PPS and the facilitation effects associated with bimodal sensory stimulations. Specifically, the distance from the body at which the multisensory facilitation effects were observed varied widely across studies, even when using the same experimental conditions (*e.g.*, from 37 to 150 cm when applying tactile stimulation on the face in co-occurrence with a looming visual stimulus; Serino et al., 2015; Serino et al., 2021). This variability implies that the multisensory facilitation effects do not consistently align with PPS, suggesting that the latter is not specifically characterised by multisensory integration. As further evidence, we recently found that visuo-tactile facilitation effects extended beyond PPS and were not correlated with it (Geers & Coello, 2023). One potential explanation is that the observed facilitation effects also reflect attentional processes, potentially expanding the spatial extent where one believes multisensory integration occurs. The typical behavioural paradigm uses looming stimuli because single-cell studies in the monkey have shown that the peripersonal neurons are particularly responsive to those stimuli as compared to other type of movements such as receding stimuli (Colby et al., 1993; Rizzolatti et al., 1981). Accordingly, behavioural estimates of multisensory facilitation have been shown to be much larger with looming than receding stimuli (except when it is centred on the hand; Noel et al., 2015; Serino et al., 2015; Stone et al., 2018; Teneggi et al., 2013). However, looming objects have also been shown to more strongly capture attention as compared to static or other types of movements (Abrams & Christ, 2006; Billington et al., 2011; Christ & Abrams, 2006; Tyll et al., 2013).

These stimuli were, for instance, given priority in a search task despite being irrelevant (Franconeri & Simons, 2003). Likewise, looming sounds have been found to elicit higher arousal levels than receding sounds, as evidenced by implicit (*e.g.*, skin conductance responses) and explicit (*e.g.*, arousal judgments) measures, and decreased RTs to a subsequent visual or auditory target, most probably as a result of the increase in arousal (Bach et al., 2009; Skarratt et al., 2009, 2014). Therefore, at least some of the observed multisensory facilitation effects may be related to the more arousing nature of approaching stimuli, compared to the non-looming stimuli of the baseline condition, facilitating thereby the detection of subsequent tactile stimulation. This so-called *looming effect* certainly intensifies with proximity. Still, it is not necessarily limited to PPS and can be observed in far space (e.g., Bach et al., 2009), potentially explaining the wide variability of the multisensory facilitation effects observed across studies, often extending well beyond the boundaries of PPS (Geers & Coello, 2023).

In this context, the present study aimed to delineate the respective role of attentional and multisensory integration processes in the multisensory facilitation effects observed around the body by requiring participants to respond to auditory or tactile stimulations in the presence of a looming visual stimulus. If the typical multisensory facilitation effects can be attributed to the looming visual stimulus being more arousing than the static (and far) stimulus of the baseline condition, then the looming visual stimulus should facilitate the detection of any event as compared to the baseline, resulting in equal facilitation for both auditory and tactile stimulations. By contrast, if the multisensory facilitation effects depend on contact anticipation grounded in the multisensory integration properties of the peripersonal neurons, they should only be observed for the tactile modality and be restricted to PPS. Assuming a combined effect of attentional and multisensory integration processes, the visual looming stimulus should facilitate the detection of both modalities to a similar extent when outside of PPS, and more prominently the tactile modality when within PPS. In light of the inconsistent findings

concerning the impact of confederates versus neutral stimuli on the extent of multisensory facilitation effects (Teneggi et al., 2013; Von Mohr et al., 2023), we seized the opportunity presented by the current investigation to explore the interplay between the attentional and multisensory integration aspects of the multisensory facilitation effects and the social nature of the visual stimulus. Specifically, we aimed to compare the effects of looming social (faces) with those of looming non-social (uniform ovoids) stimuli, thereby shedding light on the intricate relationship between social cues and the facilitation effects.

## Experiment 1 - Visuo- tactile vs. visuo-auditory integration

This experiment aimed to delineate the attentional and multisensory integration components of the facilitation effects induced by looming social and non-social visual stimuli by investigating their impact on the detection of both tactile and auditory stimuli.



### 1. Methodology

#### 1.1. Participants

Thirty-four students (17 females and 17 males, mean [*M*] age ± standard deviation [*SD*] = 23 ± 4 years) from the Université of Lille participated in this study. They were all right-handed, had a normal or corrected-to-normal vision and gave their written informed consent. Their average arm length was 75.5 ± 3.9 cm. The sample size was defined on a sample size analysis performed in G*Power indicating that 34 participants were required to detect a small interaction (Cohen's $f = 0.15$) between distance (8) and stimulation type (2) with a high power criterion (0.9) in a repeated-measures ANOVA. Note that we conducted a generalised linear mixed model (GLMM) rather than a repeated-measure ANOVA, but there is currently no satisfying method to define the sample size for this type of analysis. Given that GLMM

typically yields more statistical power (Gueorguieva & Krystal, 2004), sample sizes defined for a repeated-measures ANOVA should yield enough power in the equivalent mixed model. The research was conducted following the declaration of Helsinki and was approved by the Research Ethics Board of the University of Lille (CESC Lille, Ref. 2021-515-S95).

### 1.2. Apparatus & stimuli

The virtual stimuli were presented through an HTC Vive Pro head-mounted display in a virtual room measuring 6 x 5 x 3 m, consisting of a white floor, a grey ceiling and grey walls. The visual stimuli consisted of 3D human male and female faces displaying a neutral facial expression (social stimuli) and 3D ovoids containing the same pixels as the faces but scrambled in such a way that faces could no longer be identified (non-social stimuli). All visual stimuli had the same height and width (Figure 1). The tactile stimulation (60 ms, 3.6 V, 250 Hz) was delivered through a vibrotactile stimulator (DRV2605 Haptic Driver, Texas Instruments) fixed to the participant's chin with medical plaster. The auditory stimulation consisting of a beep (60 ms, 250 Hz) was delivered through the headphones of the headset. Both the tactile and auditory stimulations were delivered well above the detection threshold and were selected to be perceived without any anchor to a specific physical location in the external space.




**Figure 1.** 2D rendering of the virtual social and non-social visual stimuli used in Experiment 1.

### 1.3. Tasks & procedure

Participants were standing while holding a response button in their right hand, and wearing the head-mounted display. Participants were required to respond as quickly as possible whenever they felt the vibration or heard the beep while ignoring the visual stimulus. At each trial, a visual stimulus appeared at 300 cm in front of the participants for 500 ms before looming towards the participants at a velocity of 0.75m/sec. A tactile or auditory stimulation was delivered at one of the 8 following delays: 1333, 2000, 2267, 2533, 2800, 3067, 3333 or 3600 ms after the setting in motion of the visual stimulus. This means that the visual stimulus was respectively at 200, 150, 130, 110, 90, 70, 50 and 30 cm from the participant at the time the stimulation occurred. We also included unimodal trials in which a tactile or auditory stimulation was delivered while the visual stimulus remained still at 300 cm from the participant. For the sake of experiment duration, we limited the unisensory trials to three temporal delays, aligning with the shortest, intermediate, and longest delays of the bimodal trials (1333, 2800 and 3600 ms). These trials served as a baseline and enabled us to investigate the facilitation effects induced by the spatial proximity of the visual stimulus while controlling for the expectancy of stimulation or sustained attention varying with temporal delay. Finally, we also included catch trials in which no stimulation was delivered, while the visual stimulus either remained still or moved towards the participant. These catch trials were included to avoid automatic motor responses. Whenever the participant pressed the response button, the visual stimulus stopped moving, if in motion, and then remained still for 1000 ms before disappearing. The next trial started at a random delay between 800 and 850 ms following the disappearance of the previous stimulus.



The whole task consisted of 480 trials, including 128 visuo-tactile trials (2 types of stimuli x 8 delays x 8 repetitions), 128 visuo-auditory trials (2 types of stimuli x 8 delays x 8 repetitions), 48 tactile trials (2 types of stimuli x 3 delays x 8 repetitions), 48 auditory trials (2

types of stimuli x 3 delays x 8 repetitions) and 32 catch trials (2 types of stimuli x 16 repetitions), presented in random order. The trials were divided into 5 blocks of about 8 minutes intermingled with 5-minute breaks. It is worth noting that our protocol was similar to the one used in previous studies investigating multisensory integration (e.g., Noel, et al., 2020a; Pellencin et al., 2018; Serino et al., 2021; Zanini et al., 2021), except for the additional visuo-auditory condition.

### 1.4 Data Analyses

As expected, the detection rate of the stimulations was very high (tactile: 98.67 %; auditory: 98.62%). Therefore, we only analysed RTs by excluding trials with responses before stimulation (*i.e.*, false alarm: 0.32 % of the data), with no response to stimulation (*i.e.*, misses*:* 1.08 % of the data) and with RTs lower or higher than 2 SD from the mean of the participant for that specific modality of stimulation (*i.e.*, outliers: 3.32 % of the data). Catch trials were also discarded from any further analyses. RTs at baseline, *i.e.*, to the unimodal trials, were significantly faster for the tactile (mean ± standard error [SE]: 315 ± 2 ms) than the auditory (471 ± 2 ms) modality, as indicated by a paired-samples *t*-test, $t(33) = 41.77$, $p < .001$. On the other hand, RTs at baseline were similar for the social (393 ± 3 ms) and non-social (394 ± 2 ms) stimuli, $t(33) = -0.60$, $p = .555$. To control for the difference in RTs between modalities, we expressed the RT to each bimodal trial as a ratio of the RTs to the respective unisensory (tactile or auditory) trials. Notably, this facilitation index (FI) was computed for each bimodal trial as follows:

$$FI = \frac{U_{\bar{X}} - M_{xi}}{U_{\bar{X}}}$$

where $M_{xi}$ represents the RT to this particular bimodal trial and $U_{\bar{x}}$ represents the smallest mean among the mean RTs at each delay of the corresponding unisensory trials (*i.e.*, tactile

trials for a visuo-tactile trial, auditory trials for a visuo-auditory trial). Larger FI thus corresponds to greater facilitation of the tactile/auditory detection by the visual stimulus. Correcting multisensory trials with the fastest mean in the unisensory condition not only consists of the most conservative approach for computing the facilitation effect (e.g., Noel et al., 2015; Pellencin et al., 2018; Serino et al., 2015; Serino et al., 2018; Stone et al., 2018) but also accounts for potential variations in attention across participants over time. Indeed, some participants exhibited the typical expectancy effect, demonstrating shorter reaction times for the longest delay, but others displayed faster reactions for the shortest delay, potentially indicative of attention decay over time.

We then entered the FI in a linear regression with the type of Stimulation (2; tactile vs. auditory), the type of Visual stimulus (2; social vs. non-social), the Distance of the visual stimulus (8; 200, 150, 130, 110, 90, 70, 50 vs 30 cm) and their interactions as within-subject factors. As the residuals of the model were left-skewed, we first inverted the distribution by adding a negative sign to the FI values. We then added a constant (i.e., 2) to avoid negative values and finally fitted a Gamma Generalized Linear Mixed Model (GLMM) for right-skewed data using the *lme4 R* package (Bates, 2005). The model parameters were estimated using the Laplace approximation and were statistically tested using Wald's $\chi^2$. Bonferroni-corrected post-hoc pairwise contrasts were performed using the *emmeans R* package (Lenth et al., 2019). All estimates were retransformed to the original scale before being reported.

Based on the observation that the relationship between FI and Distance was most accurately represented by a second-degree polynomial (compared to linear: $LR = 33.44$, $p < .001$; and sigmoidal: $LR = 28.50$, $p < .001$), we conducted an additional analysis using a Gamma GLMM that incorporated the polynomial term. As both analyses yielded comparable results and as including the polynomial term introduces complexities in interpreting the post-hoc

pairwise contrasts, we decided to report the latter analysis in the Supplemental Material for reference.

## 2. Results

The Gamma GLMM on the FI showed a significant main effect of Distance, $\chi^2(7) = 1963.68$, $p < .001$, indicating that the facilitation effect increased with the proximity of the looming visual stimulus. The 95 % confidence intervals around the estimates of the FI at each distance indicated that the facilitation effect was significantly higher than 0 (*i.e.*, baseline) when the looming visual stimulus was at 150 cm or less from the participant ($estimate_{200}$= -0.01, 95% $CI_{200}$ = [-0.03, 0.02]; $estimates_{150\text{-}30} > 0.03$, all 95% $CI_{150\text{-}30}$ not containing 0). There was also a significant main effect of the type of Stimulation, $\chi^2(1) = 91.55$, $p < .001$, indicating that the facilitation effect was larger for the visuo-tactile (estimate ± SE: 0.11 ± 0.01) than for the visuo-auditory (0.09 ± 0.01) conditions. More importantly, these effects were embedded in a Distance by Stimulation interaction, $\chi^2(7) = 104.91$, $p < .001$. As can be seen from Figure 2, the spatial proximity of the visual stimulus facilitated the detection (greater FI) of both types of stimulation. The 95 % confidence intervals around the estimates of the FI for each distance and modality revealed that the FI was significantly higher than the baseline when the visual stimulus was at 150 cm or less of the participant, regardless of the type of stimulation (all 95% $CI_{150\text{-}30}$ not containing 0). Post-hoc pairwise contrasts between the auditory and tactile FI at each distance further revealed that the FI were not significantly different when the visual stimulus was between 200 and 90 cm from the participant (all *p*-values > .075), but that it was larger for tactile than for auditory stimulations when the visual stimulus was at 70 ($\Delta$ = 0.04 ± 0.01), *z*-ratio = 5.48, $p < .001$, 50 (0.06 ± 0.01), *z*-ratio = 8.87, $p < .001$, or 30 cm (0.07 ± 0.01), z-ratio = 9.05, $p < .001$, from the participant (Figure 2).

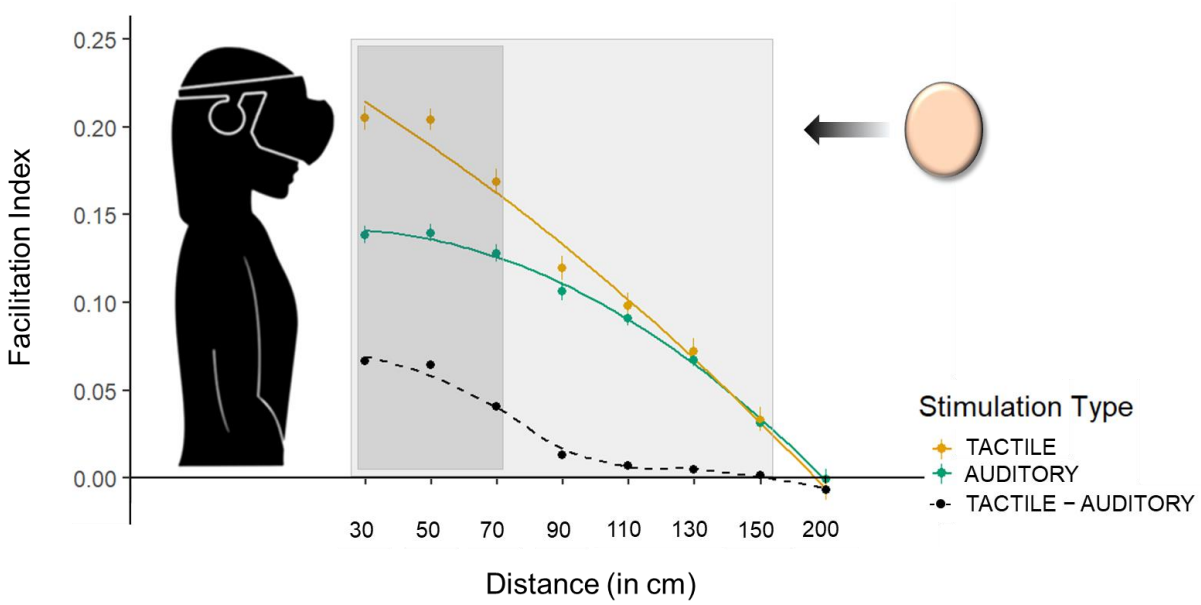


**Figure 2.** Facilitation Index (FI) as a function of the distance between the looming visual stimuli and the participants for the tactile (yellow) and auditory (green) stimulations of Experiment 1, as well as their difference (black). The dots represent the average FI and the point ranges represent the SE. The full lines represent the best-fitting second-degree polynomial function. The light grey area represents the distances (i.e., 30-150 cm) where FI was significantly different from 0 (i.e., baseline). The darker grey area represents the distances (i.e., 30-70 cm) where FI was significantly greater for the tactile than for the auditory modality.



### 3. Intermediate discussion

In Experiment 1, we investigated the effect of social and non-social looming visual stimuli on the processing of concurrent auditory and tactile stimulations. The goal was to gain a deeper understanding of the respective contribution of attentional and multisensory integration processes in the facilitation effects triggered by a looming visual stimulus. The results revealed that the spatial proximity of a looming visual stimulus, regardless of whether it was social or non-social, fastened the detection of both tactile and auditory stimulations. This facilitation effect was observed from a distance of 150 cm from the participant and intensified for both modalities as the looming visual stimulus approached the body. Hence, the facilitation

effects were observed at distances beyond the boundaries of PPS, which is typically considered to extend up to arm's length (here, 75.5 cm on average). This finding, along with the observation of facilitation effects for the auditory modality, seems to support the attentional hypothesis according to which looming visual stimuli, due to their arousing nature, enhance the detection of any event, even when situated beyond the boundaries of PPS.

However, a more pronounced facilitation effect was observed for the visuo-tactile than for the visuo-auditory condition when the visual stimulus was at 70 cm or less from the body. This finding suggests that, whenever located in PPS, the visual stimulus also triggers visuo-tactile integration, most probably through the activation of the peripersonal neurons, leading to a further enhancement of subsequent tactile, but not auditory, stimulations. Overall, our results thus support the hypothesis of a combined effect of attentional and multisensory integration processes on the processing of sensory information inside and outside PPS.



It is worth noting that the social and non-social stimuli induced the same facilitation effects both inside and outside PPS, suggesting that the social nature of the stimuli was not determinant to modulate either the attentional or multisensory integration aspects of these facilitation effects.

In Experiment 2, our objective was to gain deeper insights into the role of attentional processes by examining the impact of a looming visual stimulus on the detection of visual stimulations, i.e., in a non-multisensory stimulation context. By considering that the facilitation effects observed outside of PPS were indicative of heightened arousal associated with the looming visual stimuli, such effects should be observed across all types of stimulation, regardless of the multisensory context. We thus anticipated results for a visuo-visual condition to be similar to those found for the visuo-auditory condition: the looming visual stimulus should facilitate the detection of visual stimulation even when located outside of PPS, albeit to

a lesser extent compared to the facilitation of tactile stimulation within PPS. Additionally, to further investigate the relationship between anticipation processes and PPS, we introduced a reachability judgment task as a means to assess participants' perceived boundaries of their PPS. Indeed, if the additional facilitation observed for the tactile modality within PPS is a manifestation of contact anticipation mediated by the multisensory properties of the peripersonal neurons, then the distance at which these additional effects are observed should correspond to the boundary of PPS representation.

## Experiment 2 - Multisensory vs. Unisensory Integration

This experiment aimed to further investigate the contribution of attentional processes in the facilitation effects induced by looming visual stimuli by testing the impact of the latter on the detection of events from multiple modalities, including visual stimulations, hence in an unsystematic multisensory context. We also aimed to further investigate the link between multisensory integration and PPS by adding a reachability judgment task as a proxy for participants' representation of their PPS.



### 1. Methods

#### 1.1. Participants

Thirty-six new participants (18 females, 18 males, $M_{age} \pm SD = 21 \pm 3$ years) from the Université of Lille participated in this study. They were all right-handed, had normal or corrected-to-normal vision, and gave their written informed consent. The average arm length was 72.9 ± 5.5 cm. The sample size was defined on a sample size analysis performed in G*Power indicating that 27 participants were required to detect a small interaction (Cohen's $f = 0.15$) between distance (8) and stimulation type (3) with a high power criterion (0.9) in a repeated-measures ANOVA. The research was conducted following the declaration of Helsinki

and was approved by the Research Ethics Board of the University of Lille (CESC Lille, Ref. 2021-515-S95).

### 1.2. Apparatus & stimuli

We used the same apparatus and stimuli as in Experiment 1, except for two modifications reported hereafter. First, given that there was no difference between the social and non-social stimuli in Experiment 1, we decided to remove the non-social stimuli from this experiment. Second, we added a visual stimulation consisting of a change of colour of the whole virtual environment, except the visual stimulus, for 60 ms. This stimulation was chosen to be perceived without any anchor to a specific physical location in the external space.



### 1.3. Tasks & procedure

We used the same task and procedure as in Experiment 1, except that participants had to respond as fast as possible whenever they sensed a tactile, auditory, or visual stimulation. Moreover, we added a reachability judgment task in which participants were required to press the response button as soon as they judged being able to reach the approaching visual stimulus (same male or female avatar faces as for the multisensory integration task, *i.e.*, social stimuli of Figure 1), without performing any arm movement. Each trial started with the appearance of a visual stimulus at 300 cm in front of the participant for a duration of 500 ms, which then approached the participant at a velocity of 0.75 m/sec. Whenever the participant pressed the response button, the visual stimulus stopped moving and remained still for 1000 ms before disappearing. The next trial started at a random delay between 800 and 850 ms following the disappearance of the previous stimulus. The task consisted of 10 trials, lasted about 1 min, and was used as an index of PPS representation. It is important to emphasize that the reachability judgment task used a similar body-centred frame of reference as the multisensory integration

task. Indeed, empirical evidence has consistently demonstrated that reaching movements primarily involve a head-centred or shoulder-centred frame of reference rather than a hand-centred one (Batista, Buneo, Snyder, & Andersen,1999; Beurze, Van Pelt, & Medendorp, 2006; Lacquaniti & Caminiti, 1998; McIntyre, Stratta & Lacquaniti, 1998). It is reasonable to assume that reachability judgments are guided by the same frame of reference as actual reaching activity, especially since what is theoretically reachable by hand pertains not to what is close to the hand but rather to what falls within arm's length, originating from the shoulder.

### 1.4. Data analyses

*Multisensory Integration Task*. The detection rate of the stimulations was again very high (tactile: 98.61 %; auditory: 97.55%; visual: 96.97%). To analyse the RTs, we first excluded false alarms (0.58 % of the data), misses (1.44 % of the data), outliers (3.37 % of the data) and catch trials. Paired-sample t-tests indicated that RTs at baseline, were significantly faster for the tactile modality (334 ± 2 ms) than the RTs for the visual modality (367 ± 2 ms), the latter being, in turn, faster than the RTs for the auditory modality (501 ± 3 ms), all *p-values* < .001. Thus, we computed the FI as in Experiment 1 and entered them in a linear regression with the type of Stimulation (3; tactile, auditory vs. visual), the Distance of the visual stimulus (8; 200, 150, 130, 110, 90, 70, 50 vs 30 cm) and their interaction as within-subject factors. As the residuals were again left-skewed we applied the same transformations and analysis as in Experiment 1.

*Reachability Judgement Task.* We first excluded trials with a distance of the visual stimulus at the time of the response that was smaller or larger than 2 SD from the participant's mean and then compute the extent of perceived reachable space for each participant by averaging the remaining distances. We then compared these extents to the distance at which FI was stronger for the tactile modality than for the auditory and visual modality using one-sample t-tests. As

the extents were not normally distributed, we used non-parametric Wilcoxon signed-rank tests. As we expected an absence of difference, we also conducted the corresponding Bayesian analyses in JASP (with default values) to quantify the evidence in favour of an absence of effect ($H_0$) compared to the presence of an effect ($H_1$). These analyses provided Bayes Factors ($BF_{01}$) varying between 0 and ∞, where values above 1 provide increasing evidence in favour of the null hypothesis and values below 1 provide increasing evidence for the alternative hypothesis.

## 2. Results

### 2.1. Multisensory Integration

The Gamma GLMM on the FI showed a significant main effect of Distance, $\chi^2(7) = 1395.96$, $p < .001$, indicating that the FI increased with the proximity of the visual stimulus. The 95 % confidence intervals around the estimates of the FI at each distance revealed that the FI was significantly higher than 0 (*i.e.*, baseline) when the visual stimulus was at 150 cm or less from the participant ($estimate_{200}$= -0.01, 95% $CI_{200}$ = [-0.04, 0.01]; $estimates_{150\text{-}30} > 0.04$, all 95% $CI_{150\text{-}30}$ not containing 0). There was also a significant main effect of the type of Stimulation, $\chi^2(2) = 65.46$, $p < .001$. Post-hoc pairwise contrasts indicated that the FI was lower in the visuo-auditory (estimate ± SE = 0.09 ± 0.01) than in the visuo-tactile (0.12 ± 0.01), *z*-ratio = -7.47, $p < .001$, and visuo-visual conditions (0.11 ± 0.01), *z*-ratio = -5.11, $p < .001$, while the difference between visuo-tactile and visuo-visual conditions was marginal, *z*-ratio = 2.35, $p = .057$. More importantly, these effects were embedded in a Distance by Stimulation interaction, $\chi^2(14) = 104.81$, $p < .001$. As can be seen from Figure 3, the spatial proximity of the visual stimulus facilitated the detection of all types of stimulation. The 95 % confidence intervals around the estimates of the FI for each distance and modality revealed that FI was significantly higher than the baseline when the visual stimulus was at 150 cm or less from the participant, for the three types of stimulation (all 95% $CI_{150\text{-}30}$ not containing 0). Post-hoc

pairwise contrasts between the FI of the different modalities at each distance further revealed that FI became stronger for the tactile than for the auditory modality when the visual stimulus was at 90 cm or less from the participant, all *p*-values < .010. Moreover, FI for the tactile modality became stronger than for the visual modality when the visual stimulus was 30 cm from the participant, *z*-ratio = 4.97, $p < .001$ (Figure 3).

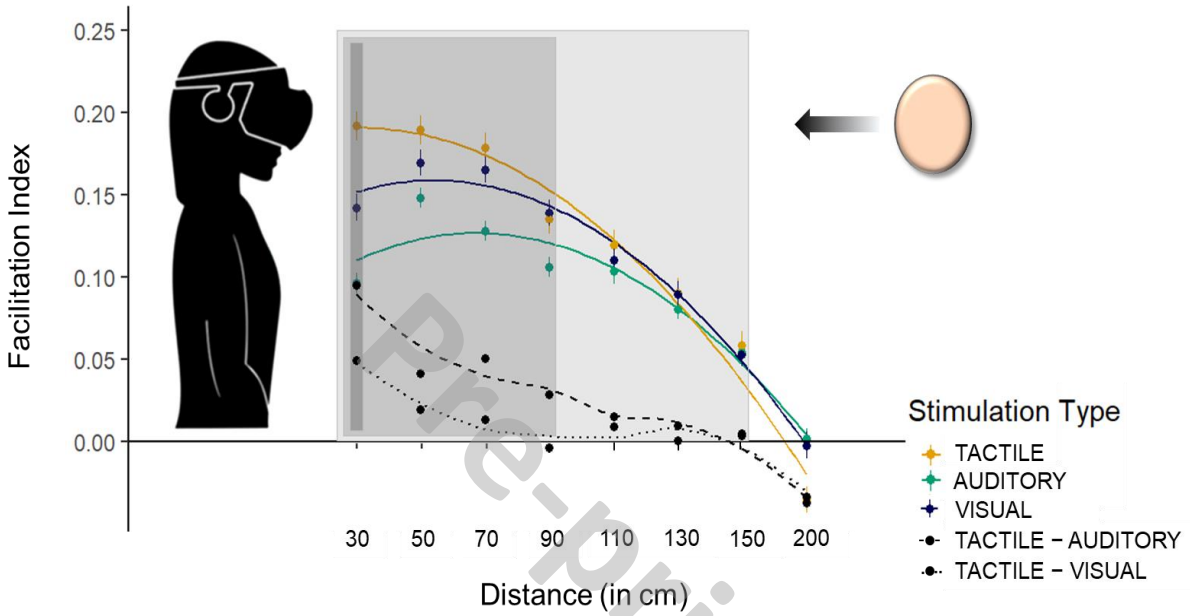




**Figure 3.** Facilitation Index (FI) as a function of the distance between the looming visual stimuli and the participants for the tactile (yellow), auditory (green), and visual (blue) stimulations of Experiment 2 as well as the difference between tactile and auditory stimulation (dashed) and between tactile and visual stimulations (dotted). The dots represent the average FI and the point ranges represent the SE. The full lines represent the best-fitting second-degree polynomial function. The light grey area represents the distances (i.e., 30-150 cm) where the FI was significantly different from 0 (i.e., baseline), the medium grey area represents the distances (i.e., 30-90 cm) where the FI was significantly larger for the visuo-tactile than for the visuo-auditory conditions, while the dark grey area represents the distance (i.e., 30 cm) where the FI was significantly larger for the visuo-tactile than for the visuo-visual conditions.

### 2.2. Reachable space

The average perceived reachable distance was 83.7 ± 32.5 cm. This extent was significantly larger from the distance at which the looming visual stimuli induced greater facilitation for the tactile than for the visual modality (i.e., 30 cm), $W$ =666, $p < .001$, $B_{01}$ = $8.02^{-10}$ but was not different from the distance at which it induced greater facilitation for the tactile than for the auditory modality (i.e., 90 cm), $W$ = 256, $p$ = .232, $B_{01}$= 2.89.

## Discussion

The present study examined the respective contribution of attentional and multisensory integration processes in the facilitation effects induced by social and non-social looming visual stimuli on the processing of tactile, auditory and visual stimulations. In summary, our findings revealed two main effects. Firstly, the looming visual stimuli induced greater facilitation in responding to tactile than visual and auditory stimulations whenever it reached a distance of about 70-90 cm or less from the body, which not only corresponds to the typical size of an arm's length (around 76 cm here) and thus PPS but also the representation of PPS as indexed by a reachability judgment task (around 84 cm here). Secondly, the looming visual stimuli induced similar facilitation effects across all three modalities when located between 200 and 90 cm from the body, thus outside PPS. These results were consistent for both the social and non-social stimuli.

The observation of greater facilitation for the visuo-tactile condition as compared to the visuo-auditory and visuo-visual conditions supports the multisensory integration hypothesis according to which visual stimuli located in PPS activate the peripersonal neurons, allowing for the anticipation of subsequent tactile stimulation through their multisensory properties (Cléry et al., 2015, 2017; Dijkerman & Medendorp, 2021; Serino, 2019). This is consistent with previous research showing an enhancement of neural response to tactile stimulation in the

presence of visual stimuli in reachable space (Rizzolatti et al., 1981), which is known to lead to faster and more accurate behavioural responses (Rowland & Stein, 2007). More generally, the stronger anticipation of touch as compared to other modalities when facing a visual object in PPS is in line with the role of PPS in organising object-directed motor actions, whether they consist in approaching incentive objects or avoiding threatening objects (Brozzoli et al., 2011; Bufacchi & Iannetti, 2018; Graziano & Cooke, 2006). Indeed, anticipating tactile feedback based on the visual properties of a nearby visual object is crucial for precise and coordinated motor actions. Similarly, anticipating physical contact with a potentially dangerous object based on its visual properties enables prompt and efficient motor reactions to this threat. Overall, our results are thus in accordance with the idea that PPS bounds visual (or auditory) information from the environment with tactile information from the body to mediate body-objects interactions (Serino, 2019). Importantly, the specific influence of looming visual stimuli on tactile stimulation cannot be attributed to inherent differences in the time processing of the sensory inputs, as the facilitation index we computed accounts for these differences.



It is worth underlining that visuo-tactile facilitation differed from visuo-auditory facilitation across the entire PPS, whereas it differed from visuo-visual facilitation only within very near PPS, specifically at a distance of 30 cm from the participant's body. Despite a continuous increase of visuo-tactile facilitation with spatial proximity, these results suggest the presence of multiple components in visuo-tactile facilitation, which depend on the location of the visual looming stimulus within PPS. Interestingly, this observation aligns with the two categories of peripersonal neurons described by Rizzolati and colleagues (1981). Among these neurons, some (46%) called *distant* peripersonal neurons, were shown to have extended visual receptive field, responding best to visual stimuli within the entire reachable space. Others (54%) called *pericutaneous* peripersonal neurons were found to have short receptive fields, responding best to visual stimuli presented within a few centimetres of the body. The

representation of very near PPS by both types of peripersonal neurons may explain the additional facilitation observed for the tactile modality in that specific region compared to the other sensory modalities (visual and auditory). As further support, Graziano and colleagues (1997) found that approximately 86% of the peripersonal neurons in the ventral premotor cortex responded when a visual stimulus was within 20 cm of the monkey's body. It is worth mentioning that the observed differences in the visuo-tactile facilitation may comply with the two functions of PPS, namely supporting intentional behaviour towards incentive stimuli and defensive behaviour towards potentially harmful stimuli (de Vignemont & Iannetti, 2015).

The second important finding of the present study is that the facilitation effects induced by visual looming stimuli started beyond PPS, and with a comparable strength for the three sensory modalities investigated. The observation of facilitation effects outside PPS aligns with some of the previous studies showing visuo-tactile facilitation effects extending far away, i.e, between 90 and 150 cm, from the body (Buck et al., 2020; Lee et al., 2021; Noel, et al., 2020; Noel et al., 2018; Pellencin et al., 208; Serino et al., 2018; Serino et al., 2021). Our results further indicate that the facilitation effects were not restricted to tactile stimulation but occurred across all the sensory modalities tested. The present data thus contradict the notion that facilitation effects induced by looming visual stimuli are solely due to contact anticipation mechanisms mediated by the multisensory properties of the peripersonal neurons which are inherently visuo-tactile or auditory-tactile and should be restricted to PPS (Cléry et al., 2017). Instead, these data support the combined hypothesis according to which the facilitation effects induced by looming visual stimuli are under the influence of additional processes. Regarding that looming stimuli have previously been shown to strongly capture attention and fasten the detection of any subsequent event (Bach et al., 2009; Skarratt et al., 2009, 2014), the most probable explanation is that part of the facilitation effect is due to the more arousing nature of the looming stimulus, although only when reaching a distance of about 1.5 m. This represents

an important outcome of the present study, as it emphasized that the facilitation effects associated with visual looming stimuli may not solely be related to PPS conceived as a motor interface between the body and the environment (Di Pellegrino & Làdavas, 2015; Wolpert & Flanagan, 2001). Additionally, it raises questions about using the current paradigm of multisensory integration, which compares the effects of a looming visual (or auditory) stimulus on tactile detection with those of a static or absent visual (or auditory) stimulus to determine the boundary of PPS (Canzoneri et al., 2012). Indeed, the additional involvement of attentional processes in these facilitation effects might lead to an overestimation of the extent of PPS and variability across studies.

An alternative interpretation for the observed facilitation effects in auditory and visual detection could involve associative learning mechanisms occurring within trimodal neurons. Given the frequent association of visual and auditory stimuli with tactile stimulation in daily experiences, there may be an anticipation of body contact through visual and auditory stimulation in the presence of looming stimuli. However, to adequately account for the disparities between modalities observed in near space, we would have to consider that the strength of association between modalities is not uniform. If auditory and visual stimulation were equally associated with tactile stimulation, any contact anticipation would logically result in facilitating tactile, visual and auditory processing similarly. Rather, the greater facilitation of tactile and visual detection than auditory detection that has been observed in near space suggests that the association between visual and tactile information is stronger than the association between auditory and tactile information. Furthermore, to address the observed distinctions between near and far space, we have to make the additional assumption that the weight of the associations between modalities is influenced by distance. Thus, although the interpretation of the data in terms of associative learning is appealing, it is imperative to acknowledge its ad hoc and speculative nature given the current state of knowledge, thus

warranting further investigation. Besides, it is worth noting that our study did not investigate the specificity of looming as compared to other types of movements such as receding stimuli. Nonetheless, prior research has already consistently demonstrated that receding stimuli aligned with body parts other than the hand either do not elicit facilitation effects or do so to a much lesser extent than looming stimuli (Noel et al., 2015; Serino et al., 2015; Stone et al., 2018; Teneggi et al., 2013). This could be attributed to their limited capacity to stimulate peripersonal neurons (Cléry et al., 2015; Colb et al., 1993; Graziano, Hu & Gross, 1997), as well as their reduced ability to capture attention (Franconeri & Simons, 2003; Skarratt et al., 2009; von Mühlenen & Lleras, 2007).

Interestingly, we found that the visual looming stimuli did not produce any facilitation effect when presented at a distance of 200 cm from the body, compared to the baseline condition where the visual stimulus was presented at 300 cm. This suggests that significant arousal elicitation by looming visual stimuli requires a certain distance from the body, even though this distance does not correspond to PPS. This is consistent with previous research showing that visual stimuli, such as human-like point-light displays, elicited an increase in skin conductance response when presented at 65 cm but not at 250 cm from the participant's body (Cartaud et al., 2018). The distance at which looming stimuli are arousing appears thus to be larger than PPS and closer to the preferred interpersonal distance, which is typically around 135 cm (Sorokowska et al., 2017). In this regard, we recently compared the three different spaces and found that the extent of visuo-tactile facilitation (without distinguishing the multisensory and attentional components; 127 cm) aligns more closely with preferred social interpersonal distance (116 cm) than with PPS (91 cm; Geers & Coello, 2023), despite a strong correlation between preferred interpersonal distance and PPS (Geers & Coello, 2022; Quesque et al., 2017). Therefore, one may suggest that the arousing nature of approaching stimuli not only serves interactions that potentially involve physical contact with objects, but also social

interactions in more distant space with visual or auditory, but no tactile consequences. Importantly, we found the same facilitation effects whether the visual looming stimuli were social (faces) or non-social (uniform ovoids). This might seem in contradiction with previous studies showing an impact of the social context on multisensory integration. However, these studies showed that that the presence of a static confederate influences the extent of the multisensory facilitation effects triggered by a non-social looming stimulus (Pellencin et al., 2018; Teneggi et al., 2013 but see Buck et al., 2020; Hoebeika, Taffou & Viaud-Delmon, 2019; von Mohr et al., 2023 for contradictory results). In contrast, our study, in conjunction with Geers and Coello (2023), represents the first exploration employing social stimuli as the visual looming stimulus of the visuo-tactile condition. Intriguingly, both of our studies failed to discern any difference between social and non-social looming stimuli, suggesting that the social nature of the looming stimulus does not easily modulate the visuo-tactile facilitation effects. The current study suggests that this finding holds true for both the contact anticipation and attentional components of the facilitation effects. However, a plausible explanation for the absence of differences may be rooted in the intermingling of social and non-social stimuli, which induced a social context at the global level of the experiment. This context could have extended its effects to non-social stimuli. Consequently, there remains a need for future studies to delve deeper into the conditions under which the nature of social agents, and the relationships with them, influence visuo-tactile integration. This could be achieved, for example, by segregating social and non-social stimuli into separate blocks, or using social stimuli with different facial expressions known to influence interpersonal distances. More broadly, a comprehensive understanding of the role of sensory facilitation effects in both objects and social interactions in both near and far space necessitates further investigation.

The present findings bear significant implications for future clinical assessments. Notably, recent studies have evidenced altered multisensory facilitation in specific clinical

populations. For instance, individuals exhibiting autistic traits (Mul et al., 2019; Noel et al., 2020; 2022), schizophrenic features (Di Cosmo et al., 2018; Ferroni et al., 2020; Lee et al., 2021) or with limb motor deficits following stroke (Bassolino et al., 2022) have demonstrated less extended multisensory facilitation effects. In light of our results, a pertinent inquiry arises regarding whether these populations genuinely exhibit a deficit of multisensory processing in peripersonal space or if the observed outcomes can be attributed to an attentional deficit. Consequently, future assessments conducted on clinical populations should incorporate a measure of the attentional component of multisensory facilitation effects. This approach would allow to elucidate whether the observed shrinkage of the facilitation effects is indicative of pathological attention, impaired peripersonal space processing, or a combination of both.



**Conclusion**

By including visuo-auditory and visuo-visual conditions in the traditional paradigm of multisensory integration, the present study revealed that the tactile modality experienced greater facilitation compared to the visual or auditory modalities when a visual stimulus was present in PPS. While this aligns with the specific role of PPS in action preparation, the results also demonstrated that visual looming stimuli induce facilitation effects not only in the tactile modality but also in the visual and auditory modalities, both within and outside PPS. This observation highlights the potential contribution of attentional processes to the observed facilitation effects in addition to contact anticipation mechanisms mediated by the multisensory properties of the peripersonal neurons. The present study thus provides novel evidence for multisensory processing in PPS to depend on the combined influence of attention and multisensory integration, having critical implications for both empirical and clinical future assessments.

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**Data availability statement**

The stimuli, data and the data analysis code are publicly available on Open Science Framework via the following link: https://osf.io/9uxa7/. No part of the study procedures or study analyses was pre-registered prior to the research being conducted. We have reported how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.



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**Supplemental Material**

**Results of the GLMM including the second-degree polynomial term**

**Experiment 1**

The Gamma GLMM on the FI showed a significant main effect of Distance, $\chi^2(2) = 1963.62$, $p < .001$, indicating that the FI increased with the spatial proximity of the visual stimulus. There was also a significant main effect of the type of Stimulation, $\chi^2(1) = 91.09$, $p < .001$, indicating a greater FI for the visuo-tactile (estimate ± SE: 0.12 ± 0.01) than visuo-auditory (0.10 ± 0.01) conditions. More importantly, these effects were embedded in a Distance by Stimulation interaction, $\chi^2(2) = 98.90$, $p < .001$, indicating that the effect of distance is stronger for the tactile ($\beta_1 = 5.23$, $\beta_2 = 0.41$) than for the auditory ($\beta_1 = 3.39$, $\beta_2 = 0.86$) modality. As the inclusion of the polynomial term requires Distance to be continuous, no further pairwise contrast could be conducted.

**Experiment 2**

The Gamma GLMM on the FI showed a significant main effect of Distance, $\chi^2(2) = 1357.51$, $p < .001$, indicating that the FI increased with the spatial proximity of the visual stimulus. There was also a significant main effect of the type of Stimulation, $\chi^2(2) = 65.21$, $p < .00$. Post-hoc pairwise contrasts indicated a lower FI for the visuo-auditory condition (0.11 ± 0.01) than for the visuo-tactile condition (0.14 ± 0.01), $z$-ratio = -4.59, $p < .001$, and visuo-visual condition (0.13 ± 0.01), $z$-ratio = -3.46, $p = .002$, while no significant difference was observed between the visuo-tactile and visuo-visual conditions, $z$-ratio = 1.12, $p = .787$. More importantly, these effects were embedded in a Distance by Stimulation interaction, $\chi^2(4) = 86.77$, $p < .001$, indicating that the effect of distance is stronger for the tactile ($\beta_1 = 4.67$, $\beta_2 = 1.36$) than for the auditory ($\beta_1 = 2.37$, $\beta_2 = 1.51$), and visual ($\beta_1 = 3.42$, $\beta_2 = 1.53$) modalities. As the inclusion of the polynomial term requires Distance to be continuous, no further pairwise contrast could be conducted.