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Emotion-inducing approaching sounds shape the boundaries of multisensory peripersonal space

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Short title: Emotion and peripersonal space

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Abstract

In order to survive in a complex environment, inhabited by potentially threatening and noxious objects or living beings, we need to constantly monitor surrounding space, especially in vicinity to our body. Such a space has been commonly referred to as one's 'peripersonal space' (PPS). In this study we investigated whether emotion-inducing approaching sound sources impact the boundaries of PPS. Previous studies have indeed showed that the boundaries of PPS are not fixed but modulate according to properties of stimuli in the surrounding environment.

In a first experiment, participants performed a simple tactile detection task on their right hand. Concurrently they were presented with intensity-changing task-irrelevant artificial sound sources perceived as approaching toward their body. The physical properties of the sound elicited emotional responses of either neutral or negative valence. **Results showed larger PPS when the approaching stimulus had negative as compared to neutral emotional valence.** In a second experiment, we used ecological sounds which content, rather than physical properties, elicited emotional responses of negative, positive or neutral valence. In agreement with the first experiment, we **found larger PPS when the approaching stimulus had negative as compared to both neutral and positive emotional valence**. Results are discussed within the theoretical framework that conceives PPS as a safety zone around one's body.

Keywords: peripersonal space, multisensory integration, emotion, auditory sources, approaching, looming

1. Introduction

The term Peripersonal space (PPS), as used in cognitive neuroscience research, commonly refers to the multisensory space around our body (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997). In the field of social psychology the term "Personal space" is often used to define the emotionally-tinged zone around the human body that people experience as "their space" (Sommer, 1959) and which others cannot intrude without arousing discomfort (Hayduk, 1983). Evidence of the multisensory coding of PPS was firstly provided by electrophysiological single cell recording in the monkey brain (Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). In 1981 Rizzolatti and colleagues described visuo–tactile neurons in the periarcuate cortex selectively responding to stimuli presented in the space immediately around the animal (Rizzolatti, et al., 1981). Following studies identified neurons integrating somatosensory information with either visual or acoustical information within PPS in the ventral premotor cortex (Rizzolatti, et al., 1981), including the polysensory zone PZ (Graziano & Gandhi, 2000), in the ventral intraparietal sulcus (Avillac, Deneve, Olivier, Pouget, & Duhamel, 2005; Duhamel, Bremmer, Ben Hamed, & Graf, 1997), in the parietal areas 7b, and in the putamen (Graziano & Gross, 1993). The existence of a similar fronto-parietal system for the multisensory coding of PPS in the human brain has been shown by different neuroimaging and neurophysiological studies (Bremmer, et al., 2001; Brozzoli, Gentile, Petkova, & Ehrsson, 2011; Cardini, et al., 2011; Gentile, Petkova, & Ehrsson, 2011; Makin, Holmes, & Zohary, 2007; Serino, Canzoneri, & Avenanti, 2011).

In both animals and humans it is largely accepted that brain specialization for PPS has several functions including to define the position of objects located near the body (Chieffi, Fogassi, Gallese, & Gentilucci, 1992; Moseley, Gallace, & Spence,

2012) and to sustain a margin of safety around one's body (Graziano & Cooke, 2006a; Niedenthal, 2007). This understanding of the PPS suggests that its boundaries can be defined in two different ways, that is, using either a metric approach or a functional approach (Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010). According to the former, all the objects located within a given physical distance (e.g., 50-60 cm) from the body will fall into the PPS. Conversely, if the functional understanding of the PPS holds, its boundaries will dynamically change according to contingent factors. To date there seems to be a large consensus on the functional hypothesis. Indeed, several studies have demonstrated that PPS boundaries can shrink or expand as a function of the properties of stimuli in the surrounding environment for example, whether the stimuli are approaching the body vs. receding it or static (Tajadura-Jimenez, Valjamae, Asutay, & Vastfjall, 2010), or whether the stimuli have the capability to elicit emotional responses or not (Vagnoni, Lourenco, & Longo, 2012).

Regarding the sensitivity of PPS boundaries to dynamic stimuli, it has been shown that PPS is more sensitive to approaching as compared to static sources. In this regard, Neuhoff and colleagues demonstrated that the terminal distance of approaching sound sources is estimated as closer than actual (Neuhoff, Planisek, & Seifritz, 2009). In the same vein, Serino and colleagues proposed a method for capturing the boundaries of PPS which involves using dynamic sounds and testing their facilitation of audio-tactile interaction (Canzoneri, Magosso, & Serino, 2012). In their study, participants responded to tactile stimuli delivered on the right hand at different delays from the onset of task-irrelevant intensity-changing sounds. These sounds, which were presented via a pair of loudspeakers placed near the hand, gave the impression of a moving source either approaching or receding from the participant's hand. Results showed that auditory stimuli perceived as moving speeded up the processing of a tactile stimulus at the hand as long as it was perceived at a limited distance from the hand, thus capturing the boundaries of PPS representation. This multisensory enhancement on PPS was stronger for approaching than receding auditory stimuli, perhaps given their larger biological salience (Tajadura-Jimenez, Valjamae, et al., 2010).

The impact of looming stimuli on PPS boundaries seems to be even stronger with emotion-inducing stimuli, as shown for threatening stimuli. This effect has been demonstrated by Vagnoni and colleagues in a behavioural study in which they used visual looming stimuli, either threatening or non-threatening (Vagnoni, et al., 2012). Participants were required to judge the time-to-collision of looming visual stimuli that expanded in size before disappearing. They found that threatening stimuli (i.e. a spider) were judged as colliding sooner as compared to non-threatening stimuli (i.e. a butterfly).

It is currently unknown whether auditory emotion-inducing looming stimuli, rather than visual, can similarly alter PPS boundaries. If we think at our everyday life, we can easily find examples suggesting that this is the case, especially, given the omnidirectional nature of spatial hearing. For instance, sounds of a growling dog are immediately perceived as threatening, and these are perceived even more threatening when the dog is running towards us and sounds are becoming louder (Tajadura-Jimenez, Valjamae, et al., 2010). Indeed, we react emotionally even when the dog is still far away and we are not still seeing it. This behaviour is likely to be paralleled by an alteration of the PPS boundaries. This example is in line with one of the functions ascribed to PPS, which refers to it as a defence space (Cooke & Graziano, 2004). According to this understanding of PPS, its boundaries would change as the surrounding environment changes, i.e. whether there are perceived sources of threat or not.

From the defence space perspective it is worth investigating whether the impact of an approaching sound source on PPS boundaries will be dependent on the perceived threat potential of this source. Experimental evidence supporting the hypothesis that negative looming stimuli can shape PPS comes from two previous studies by Tajadura-Jiménez and colleagues (Tajadura-Jiménez, Pantelidou, Rebacz, Västfjäll, & Tsakiris, 2011; Tajadura-Jimenez, Valjamae, et al., 2010). In a first study they showed that unpleasant approaching sound sources evoke more intense emotional responses than receding ones (Tajadura-Jimenez, Valjamae, et al., 2010) as revealed by electrodermal responses, electromyography and self-reported emotional experiences. This holds, however only for negative emotion-inducing sound sources but not for neutral or positive sounds. In a second study Tajadura-Jiménez and colleagues (Tajadura-Jiménez, et al., 2011) investigated the effect of listening to either positive or negative emotion-inducing music on personal space boundaries, evaluated as the comfort interpersonal distance between the participant and an experimenter approaching the participant. They found that listening to positive versus negative emotion-inducing music shrinks the representation of our personal space, thus allowing others to come closer to us. The study by Tajadura-Jiménez and colleagues, however, tested the impact of emotional auditory stimuli on personal space, as defined in social psychology, which not necessarily corresponds to the PPS, as defined in cognitive neuroscience. Moreover, in that study the auditory stimuli were only used in order to change the emotional context in which a different stimulus (the experimenter) approaches the participant.

In the present study we investigate whether emotion-inducing looming sound sources affect PPS representation. In two experiments participants were exposed to artificial and ecological sounds simulating looming (i.e. approaching) sound sources. The approaching nature of sound sources was simulated by rising intensity levels. Previous research has shown that the most salient cue for auditory motion perception is intensity change (Lutfi & Wang, 1999), and therefore, sounds rising in intensity are generally perceived as approaching sound sources (for similar procedures see: Maier & Ghazanfar, 2007; Neuhoff, 2001; Rosenblum, Carello, & Pastore, 1987; Tajadura-Jimenez, Valjamae, et al., 2010) .

In a first experiment, participants performed a simple tactile detection task on their right hand while listening concurrent task-irrelevant artificial sound sources approaching toward their body (similar procedure was used in Canzoneri, et al., 2012; Teneggi, Canzoneri, di Pellegrino, & Serino, 2013; see also Finisguerra, Canzoneri, Serino, Pozzo, & Bassolino, 2014). The spectral properties of the sounds induced emotional responses of either neutral or negative emotional valence. In agreement with the defence space perspective **we expected larger PPS when the approaching stimulus is a negative as compared to a neutral sound**. In a second experiment, we used ecological sounds, which content, rather than physical properties, elicited emotional responses of negative, positive or neutral valence. Also in this case, according to the defence space perspective, we expected a **larger PPS when the approaching stimulus is a negative, threatening sound as compared to neutral and positive sounds.**

2. Methods

2.1. Experiment 1

2.1.1. Participants

Twenty healthy subjects (17 females, mean age 21 years, range: 18–23) participated in experiment 1 and twenty-five (23 females, mean age 21 years, range: 18–23) in experiment 2. All participants were right-handed and had normal hearing, as self- reported. All subjects (students at the University of Chieti) gave their written informed consent to participate in the study, which was approved by the Ethical Committee of University "G. d'Annunzio", and was performed in accordance with the Declaration of Helsinki.

2.1.2. Artificial sounds selection and validation

Experimental stimuli were various power-law noises with flat or increasing ("looming") intensity levels of 3000 ms duration. In power-law noises the power spectral density (PSD) is changed according to the equation $1/f^{\beta}$, where β can be 0, +/-1, +/-2. Noise sounds were "white" (flat PSD), "pink" (PSD change of 1/f), "brown" (PSD change of $1/f^2$), "blue" (PSD change of f), and "violet" (PSD change of f^2). The noises were all equalized according to the sum of their power spectra in the range from 2700 to 3150 Hz, which correspond to the 16th and most sensitive frequency band according to the Bark scale (Zwicker, 1961) and ISO226 equal-loudness contours (International Organization for Standardization. Acoustics-normal equal-loudness-level contours. ISO 226:2003). The sounds were sampled at 44.1 kHz and presented by means of headphones. Sounds were manipulated by using the Soundforge 4.5 software (Sonic Foundry, Madison, WI), so that they had either flat or exponentially rising acoustic intensity from 55 to 70 dB. As previously mentioned, when rising in intensity, sounds give the impression of sources moving towards the participant's body (Canzoneri, et al., 2012; Teneggi, et al., 2013).

In a pre-experimental session a group of participants (N = 40, 21 Female, mean age = 23 years, range = 20–28) was invited to listen to all noise sounds and rate their emotional feelings using the Self-Assessment Manikin (SAM, Bradley & Lang, 1994; Lang, 1980), a test widely used in emotion research which consists of two 9-point pictorial scales. One scale serves to rate the valence or pleasantness of emotional feelings, and depicts nine manikins ranging horizontally from happy (or positive) to unhappy (or negative); the other scale, serves to rate the arousal or excitement of emotional feelings, and depicts nine manikins ranging horizontally from excited (or aroused) to calm (or relaxed). This procedure allowed selecting and validating two artificial sounds for Experiment 1, one inducing negative emotional responses and one neutral.

2.1.3. Procedure

Experimental stimuli were looming auditory stimulus lasting 3000 ms. In agreement with the results from the selection and validation part of the study (see Results section) we used the Brown and the White noises. Along with the auditory stimulation, in the 85% of trials subjects were also presented with a tactile stimulus, delivered by means of a **current constant** stimulator (Digitimer DS7A) via a pair of Ag–AgCl surface electrodes placed on the intermediate phalange of the right middle finger. The electrical tactile stimulus was a single, constant voltage, square wave pulse. The remaining trials (15% out of total) were catch trials with auditory stimulation only. Before the experiment, the intensity of the tactile stimulus was set to be clearly above thresholds, individually for each subject, as follows: intensity of the stimulator was set at the minimum value and then progressively increased until the subject referred to clearly perceive the stimulation. Then, the subject was presented with a series of 10 stimuli, at that level of stimulation, intermingled with 5 catch trials, and asked to report when he/she felt the tactile stimulus. If the subject did not perfectly perform (i.e., if he/she omitted some stimuli or answered to catch trials), intensity was further increased by 5 mA, and the procedure was repeated. Stimulus duration was 100 μsec.

Subjects were blindfolded and sat down with their right arm resting, palm down, on a table beside them. They were asked to press a button with their left index finger when a tactile target was delivered, trying to ignore the auditory stimulus. The presentation of the stimuli and the recording of participants' responses were controlled by a custom software (developed by Gaspare Galati at the Department of Psychology, Sapienza Universita` di Roma, Italy), implemented in Matlab (The MathWorks Inc., Natick, MA, USA) using Cogent 2000 (developed at FIL and ICN, UCL, London, UK) and Cogent Graphics (developed by John Romaya at the LON, Wellcome Department of Imaging Neuroscience, UCL, London, UK).

Tactile stimuli were presented with different delays with respect to the onset of the auditory stimuli. In particular, ten different delays (D1-D10) were used, ranging from 300 ms to 3000 ms, in steps of 300 ms. For each trial, the sound was preceded and followed by 1000 ms of silence. In this way, tactile stimulation occurred when the sound source was perceived at different locations with respect to the body: i.e., close to the body at high temporal delays and far from the body at low temporal delays.

Finally, in order to measure RTs in the unimodal tactile conditions (without any sound), tactile stimulation could be also delivered during the silence periods, preceding sound administration, namely at 500 ms (D0) before the beginning of the sound. The total experiment consisted of a random combination of 16 target stimuli for each temporal delay (D0-D10), for the brown and white sounds, resulting in a total of 352 trials with a tactile target, randomly intermingled with 64 catch trials. Trials were equally divided in two blocks.

2.1.4. Distance perception study

To test that subjects actually perceived the sound source (brown or white noise) at different locations according to different temporal delays in our experimental setup, we ran a sound localization experiment on 16 naïve subjects (14 females, mean age 22 years, range: 18–28). Participants sat down with their right arm resting palm down on a table beside them. They received a tactile stimulation on the index finger at one of five possible temporal delays, namely D1, D3, D5, D7 and D9 in a random series of 80 trials. At the end of each trial, they were asked to verbally indicate the perceived position of the sound source (brown or white noise) in space when they had felt the tactile stimulus, on a scale from 1 (very far) to 100 (very close). Figure 1A clearly shows that for both noises subjects progressively perceived the sound source closer to their body when the tactile stimulus was administered at successive temporal delays from D1 to D9.

2.1.5. Data analysis

Mean RTs to tactile targets were calculated for every temporal delay, separately for each sound. Mean RTs to the tactile targets at the different temporal delays were fitted to a sigmoidal function as described in Canzoneri et al. (2012) using five temporal delays obtained by averaging contiguous temporal delays. This procedure was implemented to reduce variability of each observed point in the curve. Sigmoid function solves non-linear least squares problems and returns several parameters including the central point (x_c), referring to the value of the abscissa at the central point of the sigmoid and *b* referring to the slope of the sigmoid at the central point. According to previous studies (Canzoneri et al., 2012; Teneggi et al., 2013), for each participant and each sound condition we took x_c as an estimation of the boundaries of individual PPS representation and *b* as an indication of the sharpness of the transition between the far and the near space. To test for the extent of PPS representation as a function of sound condition paired sample t-tests were run.

In preliminary analyses we fitted our data using both a linear and a sigmoidal function to test which model fitted better our data. Results showed that all the

sounds fitted better a sigmoid function than a linear function. This was further supported by statistical analyses. For each sound we compared the root mean square errors (RMSE) of the sigmoid and linear functions to test which function explained more variance. All the t-tests showed higher explained variance (i.e. lower RMSE) for the sigmoid than the linear function (all ps < 0.05).

Experiment 2

2.1.6. Stimuli and procedure

The experimental stimuli were three ecological looming sounds ('Woman Screaming'; 'Baby Laughing' and 'Brush Teeth') lasting 3000 ms. The three sounds have the capability of inducing emotional responses with negative, positive or neutral valence, respectively. They were selected from the International affective digitized sounds (IADS) database (sounds numbers: 276, 110 and 720), based on their normative emotional ratings (Bradley & Lang, 1999). The sounds were sampled at 44.1 kHz and presented by means of headphones. Sounds were manipulated by using the Soundforge 4.5 software (Sonic Foundry, Madison, WI), so that they had exponentially rising acoustic intensity from 55 to 70 dB. In this way sounds gave the impression of moving towards the participant's body. Along with the auditory stimulation, in the 77% of trials subjects were also presented with a tactile stimulus, delivered as for Experiment 1. The remaining trials (23% out of total) were catch trials with auditory stimulation only. The experimental procedure and the temporal delays between the onset of the sound and the tactile stimulation were the same as in Experiment 1 (i.e. 10 different delays from 300 ms to 3000 ms, in steps of 300 ms). In order to measure RTs in unimodal tactile condition (without any sound), tactile stimulation could be also delivered during the silence periods, preceding sound administration, namely at 500 ms (D0) before the beginning of the sound.

The total experiment consisted of a random combination of 12 target stimuli for each temporal delay (D0-D10), for each of the four sounds, resulting in a total of 528 trials with a tactile target, randomly intermingled with 160 catch trials. Trials were equally divided in four blocks. **Data were analyzed as in 2.1.5**

In order to check that the selected sounds induced the expected emotional effects, in a separate experiment we invited a subgroup of our participants (N=15) to listen to all sounds and rate their emotional feelings using SAM.

2.1.7. Distance perception study

Finally, also in this study we tested whether subjects actually perceived the emotional sound sources (negative, neutral and positive) at different locations according to different temporal delays in our experimental setup. To this aim we ran a sound localization experiment on the same subjects as in the previous distance perception study (see section 2.1.4). Participants sat down with their right arm resting palm down on a table beside them. They received a tactile stimulation on the index finger at one of five possible temporal delays, namely D1, D3, D5, D7 and D9 in a random series of 120 trials. At the end of each trial, they were asked to verbally indicate the perceived position of the sound source (negative, neutral or positive) in space when they had felt the tactile stimulus, on a scale from 1 (very far) to 100 (very close). Figure 1B clearly shows that all sounds subjects progressively perceived the sound source closer to their body when the tactile stimulus was administered at successive temporal delays from D1 to D9.

Figure 1

3. Results

3.1. Experiment 1

3.1.1. Stimuli validation

Self-reported valence and arousal SAM ratings to the different noises were used as dependent variables for a MANOVA containing as within-participants factors ‘noise colour’ (blue, brown, pink, white, violet) and ‘looming’ (on/off). The results (Figure 1) revealed that there was a significant main effect of ‘noise colour’ ($F(8, 310) = 4.04$; $p < 0.001$, $\Lambda = 0.82$) and a significant interaction between ‘looming’ and ‘noise colour’ ($F(8, 310) = 2.42$; $p < 0.05$, $\Lambda = 0.89$). These effects were mainly due to the ratings of arousal: “noise colour” was at $F(1.7, 67.9) = 8.39$; $p < 0.001$ and the interaction effect was ($F(3.3, 129.5) = 3.11$; $p < 0.05$). **Newman-Keuls** post-hoc comparisons showed several significant differences between the noise stimuli. For valence, three pairs of pink-brown, blue-violet and white-violet showed significant differences (all ps < 0.05, see Figure 2 for details). For arousal, five pairs showed significant difference: pink-brown, brown-blue, brown-white, blue-violet and violet-white (all ps < 0.05). We see that brown and pink noises are judged more arousing and less pleasant as compared to white noise. Based on these results we selected the white noise as a “neutral” sound and the brown noise as a “negative” sound.

Figure 2

3.1.2. Central Point and slope of the sigmoid functions

Three participants were discarded from the analysis because their data did not fit either the sigmoid or the linear function. Their RMSE was, indeed, higher than 2 standard deviations in both the fitting functions. A paired sample t-test was run to compare the extent of PPS representation, as defined by the central points of the sigmoid functions, in the negative sound condition and the neutral sound condition. The sigmoid central point was lower in the negative sound condition (1529 ms, Figure 3) as compared to the neutral sound condition (1731 ms; $t(16) = -2.2$; $p = 0.041$, two-tailed), suggesting that PPS boundaries

were farther from the participants when they were presented with a task irrelevant negative sound as compered to a task irrelevant neutral sound (See figure 3). Moreover, the slope at the central point tended to be higher in the negative sound (-0.43) condition as compared to the neutral sound condition (-0.23, t(16) = -1.9; p = 0.077, two-tailed).

Figure 3

3.2. Experiment 2

3.2.1. Stimuli validation

In order to assess the emotional effects of the different sounds, we asked a subgroup of our participants (N = 15; 14 females, mean age 23.5 years, range: 20–37) to rate their emotional feelings using SAM. Self-reported valence and arousal SAM ratings to the different sounds were used as dependent variables for a MANOVA containing as within-participants factor 'sound' (negative, neutral, positive, white noise), and with valence and arousal as dependent variables. The results (see Figure 4) revealed that there was a significant main effect of sound ($F(6, 82) = 8.82$; $p < 0.001$, $\Lambda = .37$), for both valence ($F(2.12, 29.63) = 15.09$; $p < 0.001$) and arousal dimensions ($F(2.37, 33.12) = 5.68$; $p < 0.01$). The 'negative' sound was rated as more unpleasant than either of the other sounds (neutral: $t(14) = 3.38$, $p < 0.01$; positive: $t(14) = 5.98$, $p < 0.001$; white: $t(14) = 2.19$, $p < 0.05$), as well as more arousing than either of the other sounds (neutral: $t(14) = 6.52$, $p < 0.001$; positive: $t(14) = 2.82$, $p < 0.05$; white: $t(14) = 3.35$, $p < 0.01$). The 'positive' sound was rated as more pleasant than the neutral and the white sounds (neutral: $t(14) = 4.21$, $p < 0.01$; white: $t(14) = 4.63$, $p < 0.01$), but not more arousing than them (all ps > 0.39). As expected, the neutral sound did not differ in pleasantness or arousal from the white noise (all ps > 0.72), thus validating the choice of the "neutral" sound as "neutral", equivalent to the sound used in Experiment 1. For this reason the white sound is not longer considered during data analysis.

Figure 4

3.2.2. Central point and slope of the sigmoid functions

Three participants were discarded from the analysis because their data did not fit either the sigmoid or the linear function. Their RMSE was, indeed, higher than 2 standard deviations in both the fitting functions. Paired sample t-tests were run to compare the extent of PPS representation, as defined by the central points of the sigmoid functions, in the different sound conditions. The sigmoid central point was lower in the negative sound condition (1325 ms; Figure 5, solid line) as compared to the neutral (1496 ms; Figure 5, dashed line) ($t(21) = -2.60$; $p = 0.02$, two-tailed) and positive sound conditions (1641 ms; Figure 5, dotted line) ($t(21) = -3.10$; $p = 0.007$, two-tailed), suggesting that PPS boundaries were farther from the participants when they were presented with a task irrelevant negative sound as compared to either a neutral and a positive sound (see Figure 5). No significant effects were found in the analysis on the slopes.

Figure 5

4. Discussion

We investigated whether emotion-inducing looming sound sources, as compared to neutral looming sound sources, have an impact on the boundaries of PPS representation. We expected changes in the size of the comfort/safety zone around one's body as a result of the emotional saliency of the sound sources approaching it. To this aim, we used a well-established multisensory task (Canzoneri, et al., 2012; Teneggi, et al., 2013) allowing to virtually demarcate the boundary of the PPS representation.

In two experiments participants were exposed to either artificial (Experiment 1) or ecological (Experiment 2) sounds, which simulated, by changes in their intensity, the rapid approach of a sound source towards the participant's body. Only emotion-inducing sounds that were unambiguously classified as either positive or negative were included as stimuli in our study. A comparable selection criterion was adopted for neutral sounds.

In Experiment 1 looming sounds were artificial sounds with either neutral or negative emotional valence, depending on the physical sound properties, specifically, spectral density changes. **Results from this experiment showed that the boundary of PPS was "located" at around 1731 ms after the onset of the neutral sound and at around 1529 ms after the onset of the negative sound (see Figure 3). That is, negative sounds produced a larger PPS as compared to neutral sounds.**

In Experiment 2 looming sounds were ecological sounds (from the IADS database) with neutral, negative or positive emotional valence. The valence of these sounds mostly depended on the semantic content of the sound. Thus, this experiment looked at whether the effect of negative valence can be generalized to other sounds found in a natural setting (Ho, Santangelo, & Spence, 2009; Ho & Spence, 2008). Importantly, differently from the first experiment, here we also looked at whether the effect on the PPS representation boundary is specific to negative valence or whether it applies to other emotion-inducing sounds of different valence (i.e. sounds with positive valence). In agreement with the previous experiment, results showed that the boundaries of PPS were "located" **at 1496 ms after the onset of the neutral sound, while they were located at 1325 ms after the onset of the negative sound.** Results from our second experiment deepen those from Experiment 1 and clearly suggest that the valence of the emotional responses induced by approaching sound sources shapes the boundaries of PPS. Indeed, this second experiment further shows that positive sounds exert an opposite effect on the boundaries of the PPS representation. Results showed that these boundaries shrank after the onset of a positive sound (they were "located" at 1641 ms after the onset of the positive sound).

Possibly, one may argue that our results are at odds with a previous study. Teneggi and colleagues (Teneggi et al., 2013), using the same paradigm of the current study, showed that fair cooperative interaction with another person brought to an expansion of PPS, while we found that positive sounds shrank PPS representation as compared to negative sound. We believe that Teneggi and colleagues' results cannot be compared to our results mostly because, although we used the same dependent variable (i.e. audio-tactile facilitation) the experimental paradigm was completely different. Here we manipulated the emotional value of the approaching stimulus while in Teneggi's study the approaching stimulus was constant while the context changed.

It is entirely possible to hypothesize that PPS expansion triggered by a fair cooperative interaction in Teneggi's study reflects an approaching behaviour. We can speculate that, as in our case there is not a clear social interaction, such a mechanism might have not been recruited. We also speculate that the expansion of PPS we observed in the negative sound condition reflects a defence mechanism aimed to keep potentially harmful stimuli far from the body.

What is important to note here is that we observed these modulations of the boundary of PPS representation by auditory-induced emotion despite the fact that both sounds and their emotional content were irrelevant to the task. How can we account for this effect?

We suggest that this effect is accounted for by the relationship between emotional sound processing and PPS representation.

Our perceptual systems are responsible of informing us on the environment and of keeping a constant margin of safety surrounding our body. Thus, they are in charge of continuously monitoring the nearby space in order to alert us of any significant events requiring an action from our side (Graziano, 2001). In this respect, the auditory system, in particular, has a number of advantages over other sensory systems suggesting that its most basic function is to act as a warning system (e.g., Juslin & Vastfjall, 2008). First, the auditory system provides us with a continuous stream of information since our ears are not "turned off" in the same way that we regularly block vision by closing our eyes (Larsson, 2005). Second, the auditory system has been characterized as a change detector that responds to certain sound properties indicating a rapid change by quickly orienting behaviour towards potential threats (Juslin & Vastfjall, 2008). This is done in a faster way than the visual system does (McDonald, Teder-Salejarvi, & Hillyard, 2000). The auditory system also complements the visual system by providing information about the events occurring outside one's visual field. With audition we can sense, without the need of turning our heads, both direct sounds emitted by different sources and their reflections from all directions in space. These reflections provide an impression of the geometry and size of the space we are in (see Larsson, 2005 and references therein).

Keeping a constant margin of safety surrounding our body is also one of the main functions stemming from PPS representation (Graziano & Cooke, 2006a; Niedenthal, 2007), and in fact, the pivotal role of auditory stimuli in shaping multisensory PPS has been shown by several neurophysiological (Graziano & Cooke, 2006b; Graziano, Reiss, & Gross, 1999), neuropsychological (Farnè & Ladavas, 2002), and psychophysical studies (Kitagawa, Zampini, & Spence, 2005; Tajadura-Jimenez, et al., 2009; Zampini, Torresan, Spence, & Murray, 2007). For instance, Farnè and Ladavas (Farnè & Ladavas, 2002) investigated crossmodal audio-tactile extinction in eighteen right brain damaged patients. Tactile stimuli were delivered on the neck while auditory stimuli were delivered either near or far from the head. Results showed that only near auditory stimuli strongly extinguished contralesional tactile stimuli. This holds true when auditory stimuli were delivered in both the front or rear space.

The relevance of auditory stimuli in shaping multisensory PPS is supported also by neuroimaging studies. There is evidence showing that approaching sounds (tones rising in intensity level), recruit a distributed neural network subserving space recognition (Seifritz, et al., 2002), including the motor and premotor cortices, the intraparietal sulcus as well as the amygdala (Bach, et al., 2008). The amygdala has been described as a warning area (Bach, et al., 2008) and as a detector of relevant events in the environment (Sander & Scheich, 2001). Neuroimaging and lesion studies have established an important role of the amygdala also for the processing of complex auditory emotional signals, such as laughing and crying (Sander & Scheich, 2001; Seifritz, et al., 2003), and fearful and angry, compared to neutral voices (Klinge, Roder, & Buchel, 2010). Furthermore, amygdala seems to play a pivotal role in the definition of the space around the body. In a seminal study, Kennedy and colleagues (Kennedy, Glascher, Tyszka, & Adolphs, 2009) reported the case of a patient with a complete amygdala lesion lacking any sense of personal space. This result has been corroborated by an imaging study showing activation of the amygdala to close personal proximity (Kennedy, et al., 2009). It is entirely possible to hypothesize that these amygdala centred distributed neural networks are recruited during our study.

From a more phenomenal perspective, the relation between emotional processing and PPS representation would be in line with the considerable amount of behavioural evidence showing that the boundary of PPS representation can be modulated by a multiplicity of factors, such as the characteristics of the stimulus (e.g., dynamic vs. static; emotionally laden vs. neutral) (Canzoneri, et al., 2012), the characteristics of the contextual environment (e.g., social vs. non-social, safety vs. threatening, Tajadura-Jimenez, Larsson, Valjamae, Vastfjall, & Kleiner, 2010; Tajadura-Jiménez, et al., 2011; Teneggi, et al., 2013) and individual personality traits (Sambo & Iannetti, 2013; Vagnoni, et al., 2012). For instance, Lourenco and colleagues (Lourenco, Longo, & Pathman, 2011) investigated whether the extension of PPS relates to individual differences in claustrophobic fear, defined as the fear of having no escape and being in closed or small spaces or rooms. They found trait feelings of claustrophobic fear predicting the size of near space. Specifically, people with larger PPS reported higher rates of claustrophobic fear than people with smaller PPS. In the same vein, individuals with high scores on trait anxiety show larger PPS than individual with low trait anxiety scores (Sambo & Iannetti, 2013).

Overall, in order to survive in a complex environment, inhabited by potentially threatening and noxious objects or living beings, as well as other individuals, first of all we need to constantly monitor the space immediately around our body. Such monitoring cannot rely on purely visual, auditory and/or emotional information. Our brain should simultaneously process all this information. The multisensory dynamic representation of PPS seems to be the best candidate for such a monitoring.

Acknowledgments

We thank Andrea Serino and Elisa Canzoneri for their helpful suggestions. M.C. and F.F. were supported by a grant from the BIAL foundation ("The body beyond the body", Ref. 41/12). M.C. and A.T-J were supported by a grant from the Volkswagen Foundation's European Platform for Life Sciences, Mind Sciences and the Humanities (''The (Un)bound Body project. Exploring the constraints of embodiment & the limits of body representation'', Ref. 85 639). A.T-J. was also supported by the ESRC grant ES/K001477/1 ("The hearing body"). A.V. was supported by Marie Curie Actions of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA GA-303172.

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FIGURE CAPTIONS:

Figure 1. Results of the sound localization experiments. Panel A refers to experiment 1, panel B refers to experiment 2.

Figure 2. Results of the stimuli validation study for Experiment 1. Mean valence and arousal ratings (in a 9-point scale) for all noise sounds. Circle: Looming sounds; Diamond: Flat sounds; P: Pink noise; BR: Brown noise; W: White noise; V: Violet noise; B: Blue noise. Error bars indicate the standard error of the means.

Figure 3. Best-fitting sigmoidal functions describing the relationship between RTs and sound distance in the Negative sound condition (Solid line) and the Neutral sound condition (dashed line).

Figure 4. Results of the stimuli validation study for Experiment 2. Mean valence and arousal ratings (in a 9-point scale) for all sound conditions (positive, negative, neutral and white). Error bars indicate the standard error of the means.

Figure 5. Best-fitting sigmoidal functions describing the relationship between RTs and sound distance in the Negative sound condition (Solid line), the Neutral sound condition (dashed line) and the Positive sound condition (dotted line).

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Figure 1
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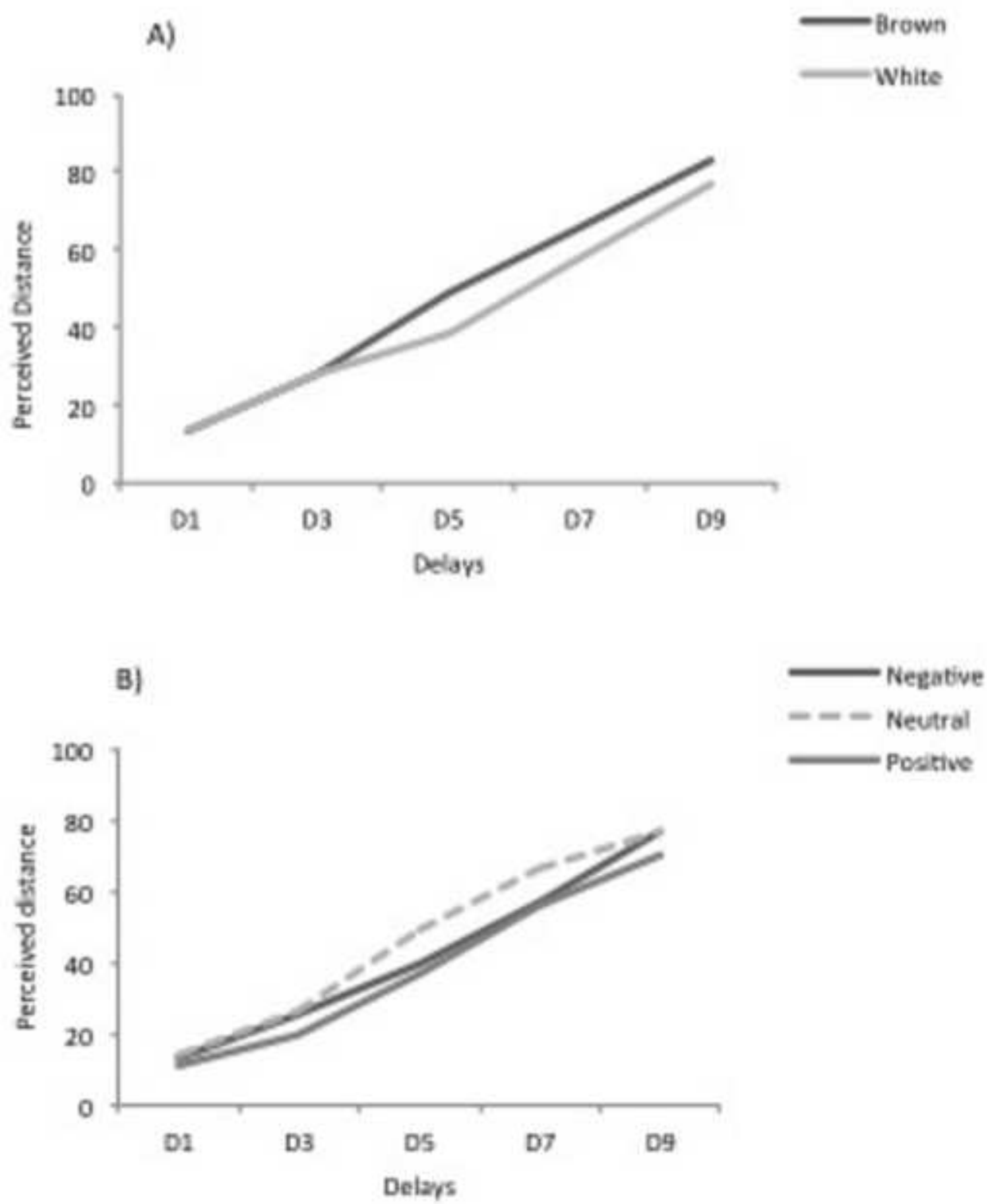

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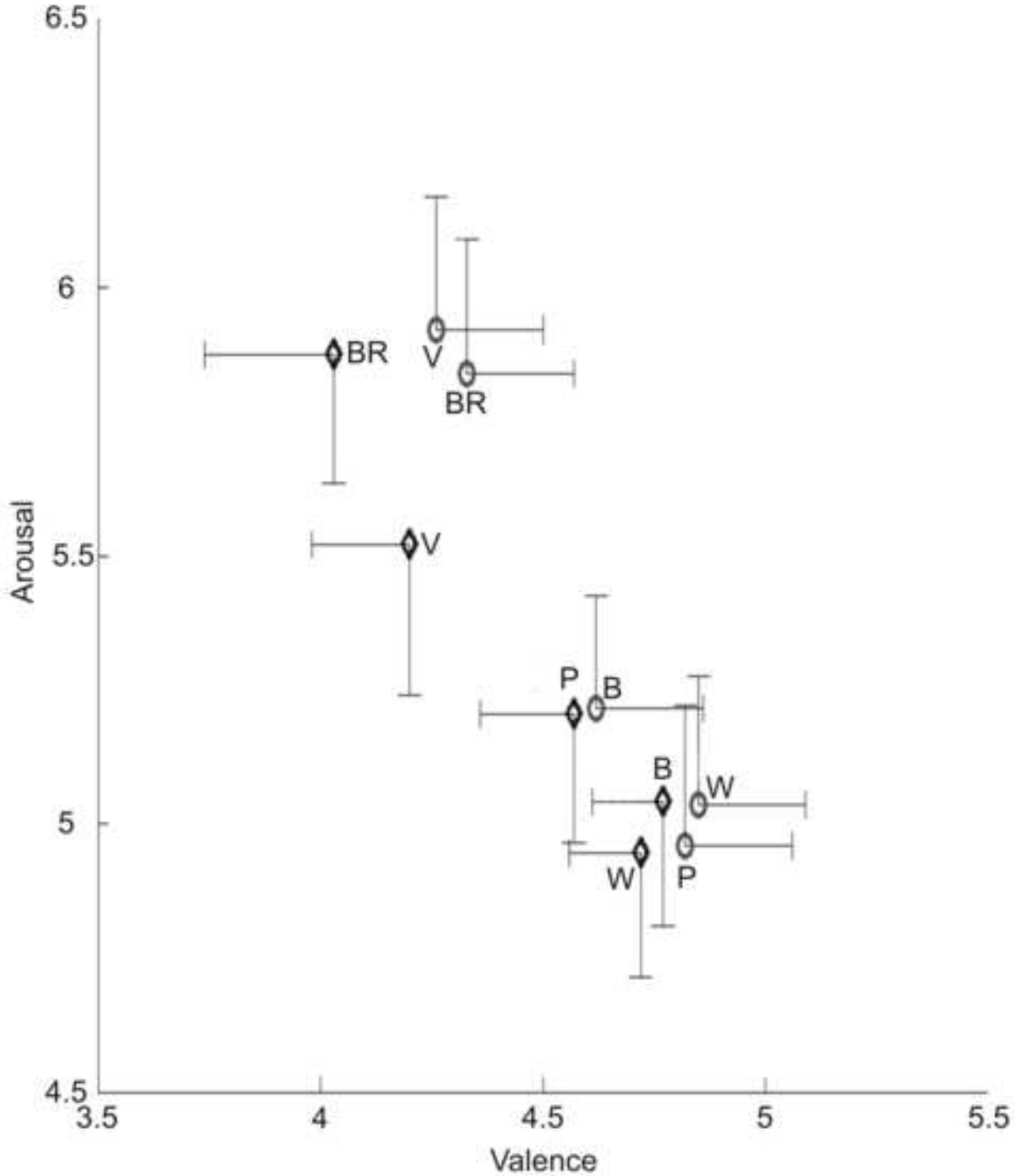

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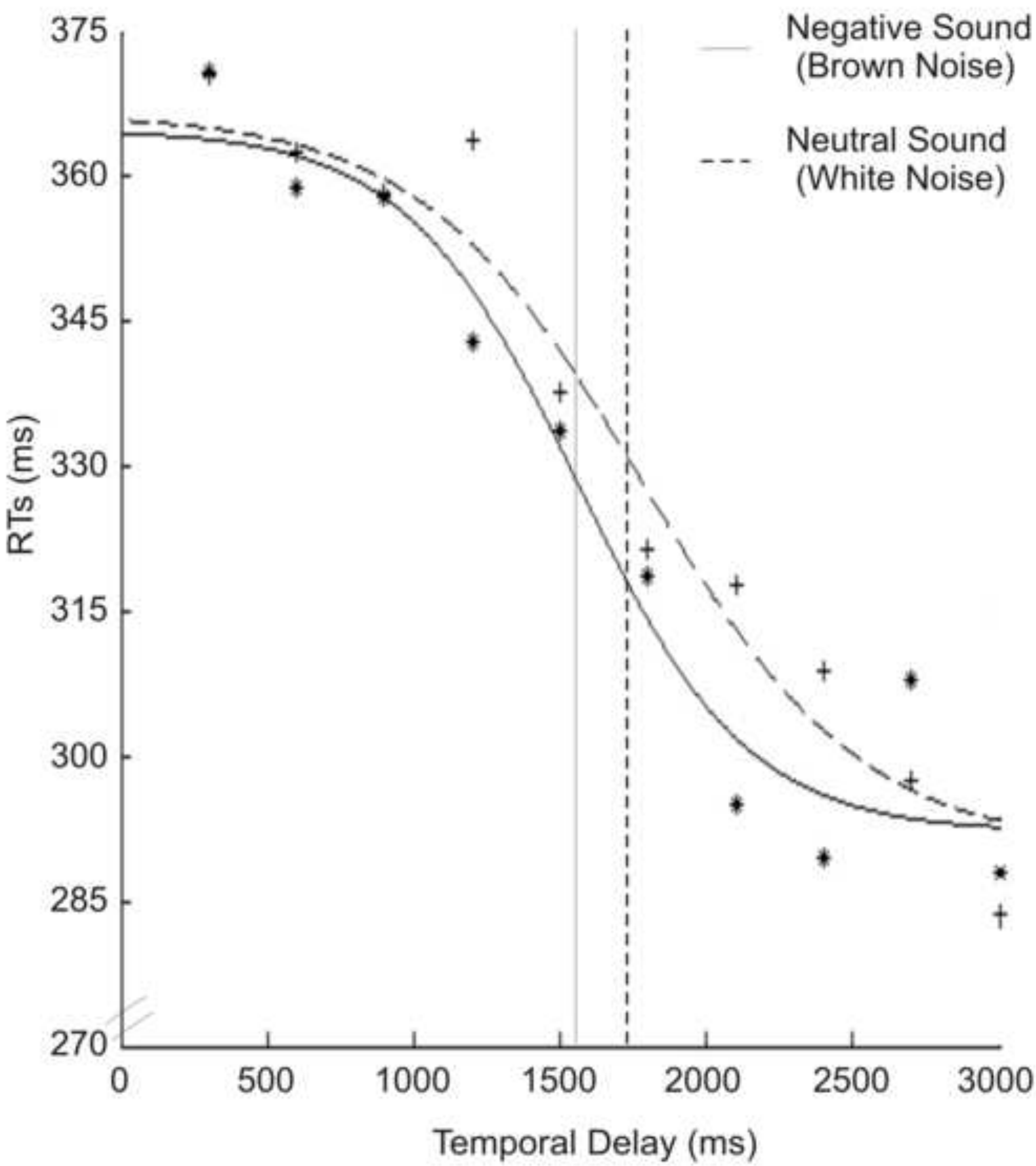

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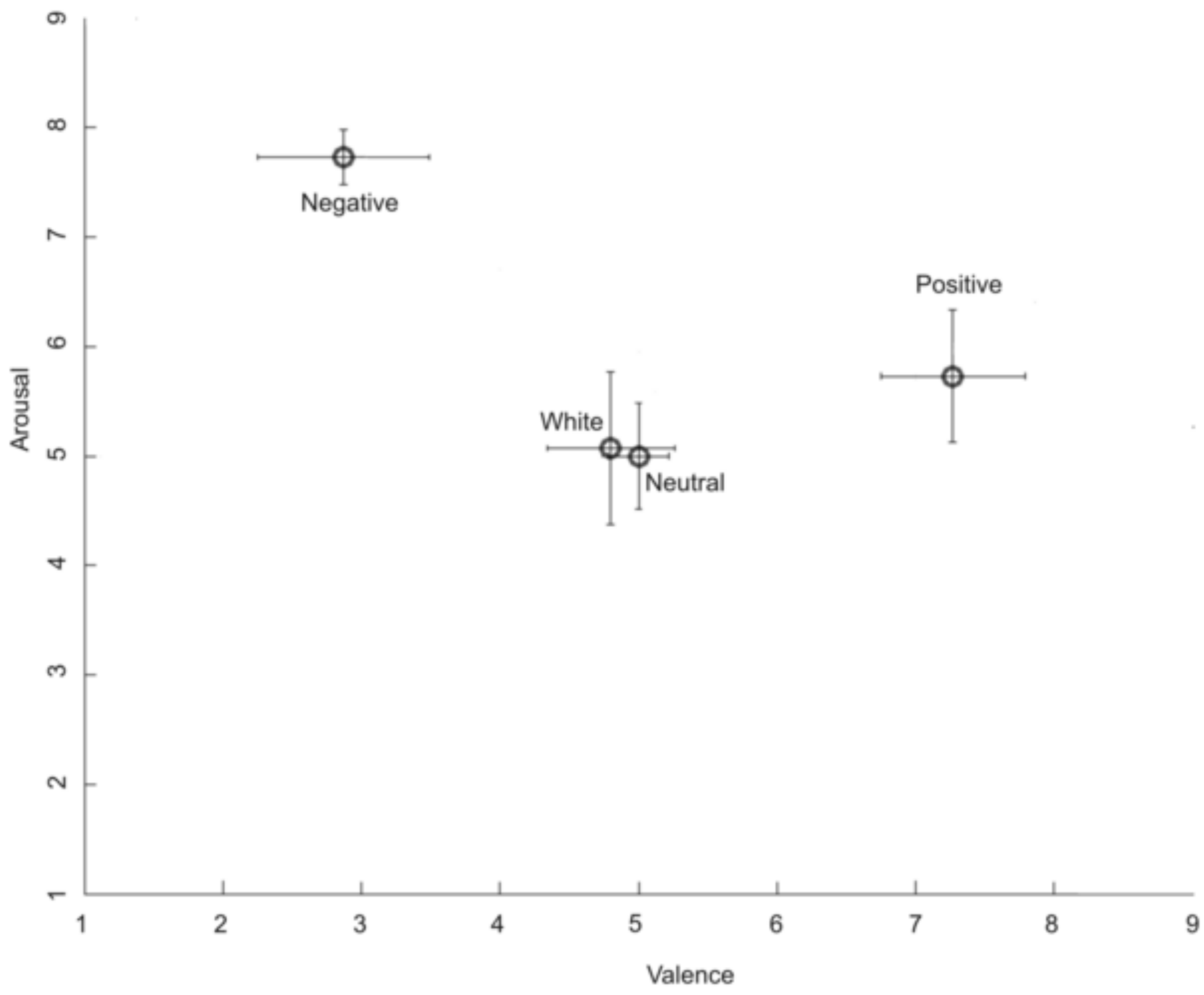

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