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# **Close is better: visual perception in peripersonal space**

**Elvio Blini, Alessandro Farnè, Claudio Brozzoli and Fadila Hadj-Bouziane**

Integrative Multisensory Perception Action & Cognition Team (ImpAct), INSERM U1028, CNRS UMR5292, Lyon Neuroscience Research Center (CRNL), and University Claude Bernard of Lyon, Lyon, France

Correspondence:

Elvio Blini and Fadila Hadj-Bouziane, INSERM U1028, CNRS UMR5292, Lyon Neuroscience Research Center, ImpAct Team, 16 Avenue Doyen Lépine 69500 Bron, France. Emails: [elvio.blini@inserm.fr](mailto:elvio.blini@inserm.fr) ; [fadila.hadj-bouziane@inserm.fr](mailto:fadila.hadj-bouziane@inserm.fr)

25

## Abstract

26 The neuroscientific approach to PeriPersonal Space (PPS) stems directly from electrophysiological  
27 studies assessing the response properties of multisensory neurons in behaving non-human primates. This  
28 multisensory context fostered frameworks which: i) stress the PPS role in actions (including defensive  
29 reactions) and affordances, which are optimally performed through multiple sensory convergence; ii)  
30 largely make use of tasks that are multisensory in nature. Concurrently, however, studies on spatial  
31 attention reported proximity-related advantages in purely unisensory tasks. These advantages appear to  
32 share some key PPS features. Activations in brain areas reported to be multisensory, indeed, can also be  
33 found using unimodal (visual) paradigms. Overall, these findings point to the possibility that closer  
34 objects may benefit from being processed as events occurring in PPS. The dominant multisensory view  
35 of PPS should therefore be expanded accordingly, as perceptual advantages in PPS may be broader than  
36 previously thought.

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## Highlights

- 39 • The neuroscientific approach to PPS originates from lines of research devoted to the study of  
40 the properties of multisensory neurons.
- 41 • The dominant multisensory context largely influenced the use of tasks that are multisensory in  
42 nature.
- 43 • Studies on spatial attention concurrently reported proximity-related advantages in purely  
44 unisensory (visual) tasks.
- 45 • Brain activations observed in purely visual paradigms tightly overlap with multisensory areas  
46 coding for PPS.
- 47 • Seeing PPS as a multisensory-only interface may be limiting, and its role may be broader than  
48 previously thought.

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52 **Keywords:** Peripersonal Space; Multisensory; Unisensory; Visual Streams; Attention; Spatial  
53 Attention; Depth;

54

## 1. Peripersonal space: the multisensory origins

56 The intuition that the space closely surrounding our body is somehow special has a rather long history  
57 (Hall, 1966; Hediger, 1950). For example, Hall (1966) sketched several rough boundaries which, from  
58 a social perspective, are functional to different types of interaction (e.g. intimate, up to 45 cm, personal,  
59 up to 1.2 m, social, up to 3.6 m, or public; see de Vignemont, 2018). However, it is probably the seminal  
60 study of Rizzolatti, Scandolara, Matelli, & Gentilucci (1981) that shaped and gave impulse to the vast  
61 literature about the newly termed PeriPersonal Space (PPS; also see Hyvärinen & Poranen, 1974).  
62 Rizzolatti and colleagues recorded, in macaque monkeys, the responses of neurons located in the  
63 periarculate cortex – part of the frontal lobe that receives input from associative sensory areas. The  
64 authors found a substantial proportion of neurons that were reliably coding for visual stimuli appearing  
65 in PPS, defined operationally as the space immediately surrounding the body (e.g. 10 to 30 cm).  
66 Strikingly, the vast majority of these visual neurons had bimodal (visual and somatosensory) receptive  
67 fields that were in register with the corresponding somatosensory area (e.g. neurons responding to visual  
68 stimuli close to the mouth had a tactile counterpart on the mouth), an observation that has been  
69 confirmed and extended afterwards to other brain regions (e.g. putamen, ventral intraparietal area,  
70 premotor cortex; Colby, Duhamel & Goldberg, 1993; Fogassi et al., 1996; Graziano & Cooke, 2006;  
71 Graziano & Gross, 1993). This seminal finding gave rise to a first neuroscientific approach to study  
72 PPS, with a dominant multisensory perspective, as well as a framework to guide cognitive models.

73 The original account of Rizzolatti et al. (1981) advocated that the role of these bimodal neurons may  
74 essentially be action-oriented (also see Murata et al., 1997). PPS is the only region of space in which we  
75 can act on, reach, or manipulate objects directly: a tight link between visual and somatosensory input is  
76 particularly expected in PPS, because it may contribute to the efficiency of our goal-directed actions, on  
77 one hand, and it may be shaped by the continuous experience of simultaneous multisensory stimulations,  
78 on the other hand. Arguably, studies exploring the effect of tool-use training (Iriki, Tanaka, & Iwamura,  
79 1996; Maravita & Iriki, 2004), which can expand the region of space upon which we can purposefully  
80 act, were largely inspired by this formulation. In the seminal study of Iriki et al. (1996), macaque  
81 monkeys were trained to reach objects with a rake while the activity of multisensory neurons in the  
82 postcentral gyrus was recorded. The authors found that, during tool-use, the visual receptive field of  
83 these neurons was enlarged up to covering the tip of the rake (Iriki et al., 1996). Tool-use has been  
84 exploited ever since to probe the plasticity of PPS representation and body schema (Berti & Frassinetti,  
85 2000; Cardinali et al., 2009; Farnè & Làdavas, 2000; Maravita, Spence, Kennett, & Driver, 2002;  
86 Sposito, Bolognini, Vallar, & Maravita, 2012), a closely related – yet different – representation of the  
87 body for actions (Cardinali, Brozzoli, & Farnè, 2009).

88 Defensive actions are particularly important responses that can be accomplished in PPS (Graziano &  
89 Cooke, 2006). Escape from a predator or a threatening stimulus has a much more pronounced

90 motivational priority than the needs for food or mating, yet the sight of a threat is not generally sufficient  
91 to activate defensive responses: the threat must also violate some safety boundary around the body,  
92 termed flight distance (Hediger, 1950), and be perceived as intrusive (Graziano & Cooke, 2006). PPS  
93 has also been conceptualized as a system evolved to be highly specialized in coding and maintaining  
94 this safety boundary (Graziano & Cooke, 2006), a task for which multisensory interactions are  
95 paramount. Think, for example, to looming objects: potentially harmful objects approaching enhance  
96 automatically the tactile sensitivity of the body part (and nearby body parts) upon which contact is  
97 expected to happen (Cléry, Guipponi, Odouard, Wardak, & Ben-Hamed, 2015; Colby, Duhamel, &  
98 Goldberg, 1993; Neppi-Mòdona, Auclair, Sirigu, & Duhamel, 2004). Stressing the defensive function  
99 of PPS does not contradict the first, action-related formulation. This account has provided instead fertile  
100 ground for studies extending the notion of PPS plasticity to include interpersonal distance regulation  
101 depending on emotion- or stress-related stimuli. For example, Ruggiero et al. (2017) presented to healthy  
102 participants visual avatars depicting different facial expressions with emotional valence (e.g. happy vs  
103 angry), approaching them in an immersive virtual reality environment. They asked participants to press  
104 a button as soon as the distance of visual avatars was felt as uncomfortable, thus delineating a comfort  
105 distance or zone. Participants showed enlarged comfort zone for the avatars signaling anger (Ruggiero  
106 et al., 2017). The magnitude of this enlargement can be predicted on the basis of individuals' autonomic  
107 responses (Cartaud, Ruggiero, Ott, Iachini, & Coello, 2018) and is modulated by personality traits such  
108 as the level of anxiety (Sambo & Iannetti, 2013). Overall, this picture is coherent with the notion that  
109 the presence of threatening cues within the close space surrounding us prompts avoidance behaviors  
110 (Ruggiero et al., 2017; also see Ferri, Tajadura-Jiménez, Väljamäe, Vastano, & Costantini, 2015;  
111 Teneggi, Canzoneri, di Pellegrino, & Serino, 2013). As such, PPS may help us efficiently move towards  
112 (to reach) or away from (to avoid) elements of our close environment. Separating the two functions of  
113 PPS into action- or defense-related is therefore probably artificial (de Vignemont & Iannetti, 2015). A  
114 more general take could assume a flexible organization of PPS that would depend on current task and  
115 environmental constraints (e.g. Bufacchi & Iannetti, 2018). It is worth stressing, however, that both  
116 formulations firmly build on, and were originally put forward to accommodate for, the multisensory and  
117 distance-tuned properties of neurons ascribed to PPS.

118 It would not be surprising, at this point, to note that most of the tasks devised to probe PPS-related  
119 processing involve bimodal sensory stimulations. One common scenario involves the presentation of  
120 one to-be-discriminated tactile stimulus coupled with an irrelevant visual or auditory one, delivered in  
121 either an overlapping, close, or distant position in space (Brozzoli, Pavani, Urquizar, Cardinali, & Farnè,  
122 2009; Canzoneri, Magosso, & Serino, 2012; Maravita, Spence, & Driver, 2003; Spence, Pavani, &  
123 Driver, 2004; Teneggi et al., 2013). These tasks have shown that, when both stimuli are overlapping in  
124 space and time, stronger multisensory interaction occurs: neural and behavioral responses are therefore  
125 enhanced, resulting in advantages (Makin, Holmes, Brozzoli, & Farnè, 2012). This effect is maximal

126 near the body (i.e. where touch is delivered) and decreases as a function of the distance at which the  
127 irrelevant stimulus is presented. Psychophysical modelling of this decay allows one to estimate a rough  
128 point of “indifference”, in which multisensory interaction no longer occurs, and thus to functionally  
129 identify two seemingly different regions of space (Canzoneri et al., 2012; Noel et al., 2015; Teneggi et  
130 al., 2013). For example, Canzoneri et al. (2012) measured response times for tactile discrimination of  
131 stimuli presented with a concurrent dynamic sound (i.e. perceived to be looming or receding, and at  
132 different distances from the delivered touch). The results showed an audio-tactile interaction effect,  
133 stronger with approaching sounds, that was maximal close to the stimulated hand. Psychophysical  
134 modelling further suggested that a sigmoidal function could adequately capture this decay, and the  
135 inflection point of the curve (the aforementioned “indifference point”) was taken as a proxy for the  
136 putative limit and extension of PPS. This approach was proven fertile and capable to highlight the  
137 peculiar plasticity of PPS. For example, it was exploited to show that sounds associated – for either  
138 physical or semantic properties – to negative emotions or contents are capable to push the PPS  
139 boundaries farther away (Ferri et al., 2015), in agreement with the PPS role in maintaining a safety zone  
140 around the body.

141 The wide use of multisensory tasks to probe PPS processing is paradigmatic of its conception as the  
142 region of space in which multisensory interactions occur; it is certainly the case for the integration of  
143 touch with other sensory stimulations, as touch clearly cannot happen in extrapersonal space. Indeed,  
144 PPS is inherently multisensory. However, this does not preclude the existence of unimodal advantages  
145 tied to PPS-specific processing. This chapter will review recent evidence for the existence of such  
146 unisensory (visual) advantages. However, before tackling this emerging field, we deem useful a brief  
147 overview of the literature concerning the distribution of spatial attention in depth.

148

## 149 **2. Peripersonal space and attention: the inextricable link?**

150 It is hard, perhaps impossible, to tease apart whether depth-specific neural and behavioral modulations  
151 results from enhanced attentional processing close to the body or rather to a dedicated system for PPS  
152 (perceptual) processing (but see Makin, Holmes, Brozzoli, Rossetti, & Farnè, 2009; Reed, Leland,  
153 Brekke, & Hartley, 2013, for dissociations between effects depending on mere hand proximity and  
154 orienting of attention). This literature, however, allows us to access and appreciate several findings that,  
155 far from denying a privileged role of PPS in perception, may increase our understanding of PPS-specific  
156 unisensory advantages.

157 Spatial and hemispheric asymmetries hold a special place within the literature on human perceptual and  
158 attentional system(s). General consensus has been reached on the notion that attention is not uniformly  
159 distributed along the three orthogonal axes (Gawryszewski, Riggio, Rizzolatti, & Umiltà, 1987; Shelton,

160 Bowers, & Heilman, 1990). However, the majority of experiments has been carried exploiting two  
161 dimensional screens, thereby neglecting the sagittal (near-to-far) plane (but see Couyoumdjian, Nocera,  
162 & Ferlazzo, 2003; Losier & Klein, 2004; Plewan & Rinkenauer, 2017).

163 As notable exceptions, few studies exploited cued detection tasks with stimuli appearing at different  
164 distances (Couyoumdjian et al., 2003; Gawryszewski et al., 1987; Losier & Klein, 2004). The first notion  
165 drawn from these studies is that spatial attention can be displaced along the sagittal plane just like it can  
166 be displaced along the horizontal and vertical planes (Couyoumdjian et al., 2003; Gawryszewski et al.,  
167 1987; Losier & Klein, 2004), as seen by cueing validity effects (i.e. better performance when cues and  
168 targets appear in the same region of space, and decreased performance when positions are incongruent).  
169 Second, participants are faster in responding to stimuli appearing close to their body, in PPS, suggesting  
170 that more attentional resources are allocated there (Gawryszewski et al., 1987; Plewan & Rinkenauer,  
171 2017). A more specific manifestation of this phenomenon has been described for the space close to the  
172 hands (Reed, Grubb, & Steele, 2006). Reed, Grubb, & Steele (2006) used a purely visual covert attention  
173 paradigm, a cued detection task like the ones described above, in which the only experimental  
174 manipulation was the position of the participants' hand (either close to left- or right-sided targets); thus,  
175 also in this case the task had no explicit cross-modal component, being confined to the visual modality.  
176 Visual stimuli were detected faster when appearing closer to the perceived position of the hands (near-  
177 hand effect). This applied also when visual input was lacking, i.e. when the hand was occluded, the  
178 proprioceptive input appeared sufficient for this effect to emerge (but see, for contrasting evidence on  
179 the role of hand proprioception, Blini et al., 2018; Di Pellegrino & Frassinetti, 2000; Làdavas, Farnè,  
180 Zeloni, & Di Pellegrino, 2000). Hand position alone could, indeed, modulate both early and late  
181 attention-sensitive components of brain activity in a subsequent experiment exploiting event-related  
182 potentials (Reed et al., 2013). Behavioral results were later extended with different tasks (e.g. visual  
183 search, inhibition of return, attentional blink), all consistently showing that visual and attentional  
184 abilities are altered near the hands (Abrams, Davoli, Du, Knapp III, & Paull, 2008).

185 It is interesting to notice that the accounts proposed to frame these results also call into cause the role of  
186 attention in maximizing action efficiency or in monitoring the nearby space for defensive purposes  
187 (Abrams et al., 2008). The maintenance of a defensive space, indeed, would necessarily involve  
188 monitoring of the nearby environment, a mental representation of it, and ultimately attentional resources  
189 to be constantly deployed (Graziano & Cooke, 2006). The question as to whether such a – constantly  
190 active – monitoring is biologically and evolutionarily plausible remains open, as this could come at very  
191 high costs for already limited resources. In addition, the monitoring of looming objects, with respect to  
192 receding ones, would be privileged because more likely to result in an impact with the body (Cléry et  
193 al., 2015; Neppi-Mòdona et al., 2004). Looming objects are indeed known to strongly capture  
194 visuospatial attention in human (Franconeri & Simons, 2003; Lin, Murray, & Boynton, 2009) and non-  
195 human primates (Ghazanfar, Neuhoff, & Logothetis, 2002; Schiff, Caviness, & Gibson, 1962), and cause

196 increased multisensory interaction (Canzoneri et al., 2012; Maier, Neuhoff, Logothetis, & Ghazanfar,  
197 2004), typically attributed to PPS-specific processing. Similarly, threatening stimuli or cues strongly  
198 capture and hold attention (Armony & Dolan, 2002; Koster, Crombez, Van Damme, Verschuere, & De  
199 Houwer, 2004). It could thus be argued that this specificity may explain, at least in part, the effects  
200 reported over PPS signatures (i.e. extended PPS limits, Ferri et al., 2015; but see Makin et al., 2009, for  
201 evidence of a dissociation). Another possibility would be that the domain-general mechanism of spatial  
202 attention, and cross-modal attention in particular (e.g. Eimer, Velzen, & Driver, 2002), may exploit the  
203 neural circuits specialized for PPS, as initially suggested (Làdavias, Pellegrino, Farnè, & Zeloni, 1998).  
204 Disentangling these – potentially not mutually exclusive – alternatives may be difficult, especially with  
205 purely behavioral paradigms. Yet, better identifying the specific roles played by attention vs. PPS  
206 perception is likely to provide valuable contributions to our understanding of the mechanisms that today  
207 are indistinguishably gathered within the PPS label. At any rate, phenomena like the near-hand effects  
208 typically represent instances in which advantages for stimuli presented close to the body occur in purely  
209 unisensory tasks.

210

### 211 **3. Neural bases of peripersonal multi- (and uni-) sensory processing**

212 The functional linkage between PPS and actions, supported by neurophysiological and anatomical  
213 evidence from primate work (see for review, Makin, Holmes, Brozzoli, & Farnè, 2012), prompted the  
214 idea that visual processing in PPS would mainly rely on the dorsal visual stream, optimized for action,  
215 whereas visual processing beyond it would mainly rely on the ventral stream, optimized for perception  
216 (Milner & Goodale, 2008; Previc, 1990). As the dorsal stream recruits more extensively parietal  
217 networks and magnocellular neurons – that are highly specialized in responding to rapid changes in the  
218 visual scene in spite of their low resolution – this is also well fitting with the PPS role in monitoring a  
219 zone around the body. One could argue that, at least in some conditions, it would be better to ward off  
220 an insect close to us before knowing whether it is a wasp or a ladybird. This notion has been supported  
221 by behavioral studies showing faster detection times for stimuli occurring close to the body or the hands  
222 (Gawryszewski et al., 1987; Plewan & Rinkenauer, 2017; Reed et al., 2006; but see Makin, Brozzoli,  
223 Cardinali, Holmes, & Farnè, 2015). Furthermore, studies have shown that performance in tasks requiring  
224 speeded temporal-gap detection improves in the near-hand space (Goodhew, Gozli, Ferber, & Pratt,  
225 2013; Gozli, West, & Pratt, 2012), whereas performance in spatial-gap tasks is hampered (Gozli et al.,  
226 2012); this has been discussed as coherent with a general magnocellular advantage for PPS processing  
227 (Bush & Vecera, 2014; Goodhew, Edwards, Ferber, & Pratt, 2015, for a review).

228 However, on the other side of the coin, on the bases of this account performance benefits in fine-grained  
229 discrimination tasks could be predicted to occur beyond PPS, where the ventral pathway would play a  
230 more important role. Parvocellular neurons – with their small and contrast-sensitive receptive fields –

231 appear indeed ideal matches to contribute to object identification, especially because, in everyday life,  
232 the size of an object (retinal size) scales with distance. In other words, we would be better in  
233 discriminating wasps from ladybirds when the insect is far; in this case we could afford time to prepare  
234 an optimal response, shaped according to the significance of the threat (we would need a fast, automatic  
235 response when too late, the insect being already close). However, this view has been recently challenged,  
236 as visual discrimination appears to actually improve as well in PPS (Blini et al., 2018). Though this  
237 classic account is well supported by neuropsychological and neurophysiological evidence, the  
238 dichotomy between ventral and dorsal pathways is not meant to be strict (Milner & Goodale, 2008).  
239 Accumulating evidence specifically point to the fact that the dorsal stream contains objects  
240 representations that are to some extent independent from those in the ventral stream, and capable to  
241 contribute to human perception (Freud, Ganel, et al., 2017; Freud, Plaut, & Behrmann, 2016; Quinlan  
242 & Culham, 2007; Wang, Li, Zhang, & Chen, 2016). One recent study, for example, has shown that  
243 fundamental properties of shapes can be reliably decoded from posterior parietal regions, whose  
244 activation profile appears correlated with recognition performance (Freud, Culham, Plaut, & Behrmann,  
245 2017), suggesting a functional role in shape identification. Candidate areas appear to be a set of  
246 subcortical (e.g. putamen, Graziano & Gross, 1993) and fronto-parietal cortical areas (i.e. inferior  
247 parietal and premotor, Brozzoli, Gentile, & Ehrsson, 2012; Brozzoli et al., 2011; di Pellegrino &  
248 Làdavas, 2015; Fogassi et al., 1996; Graziano & Cooke, 2006; Lloyd, Morrison, & Roberts, 2006)  
249 associated with PPS processing. For example, Brozzoli et al. (2011) presented, to healthy participants  
250 lying supine inside a Magnetic Resonance Imaging (MRI) scanner, 3D objects either close (3 cm) or far  
251 (100 cm) from their outstretched hand (or in the same physical/visual position but while their hand was  
252 resting unseen on the torso). The authors capitalized on a robust property of neuronal responses  
253 measurable using functional MRI, that is neural adaptation: neural activity is reduced when a stimulus  
254 feature is repeated, but only for a subpopulation of neurons that is selective for the repeated feature itself  
255 (Grill-Spector, Henson, & Martin, 2006). The authors found evidence of neural adaptation only when  
256 visual stimuli appeared close to the outstretched hand, but not when the stimuli appeared in the same  
257 spatial position while the hand was placed on the torso (Brozzoli et al., 2011). Thus, in agreement with  
258 neurophysiological investigations in monkeys, they confirmed in humans that a set of interconnected  
259 premotor and posterior parietal regions specifically encode the position of visual objects close to the  
260 body, in hand-centered coordinates. It is interesting to note that the set of areas described by Brozzoli et  
261 al. (2011) tightly overlap with regions reported to respond to multisensory stimulations occurring in PPS  
262 (Brozzoli et al., 2012; Gentile, Petkova, & Ehrsson, 2010; Lloyd et al., 2006; Macaluso & Driver, 2005;  
263 Makin, Holmes, & Zohary, 2007), and yet were obtained via a purely visual stimulation. This supports  
264 the idea that, though PPS is inherently multisensory, enhanced perceptual processing in it can be  
265 expected to occur also for unimodal (e.g. visual) stimuli.

#### 4. Visual discrimination advantages in peripersonal space

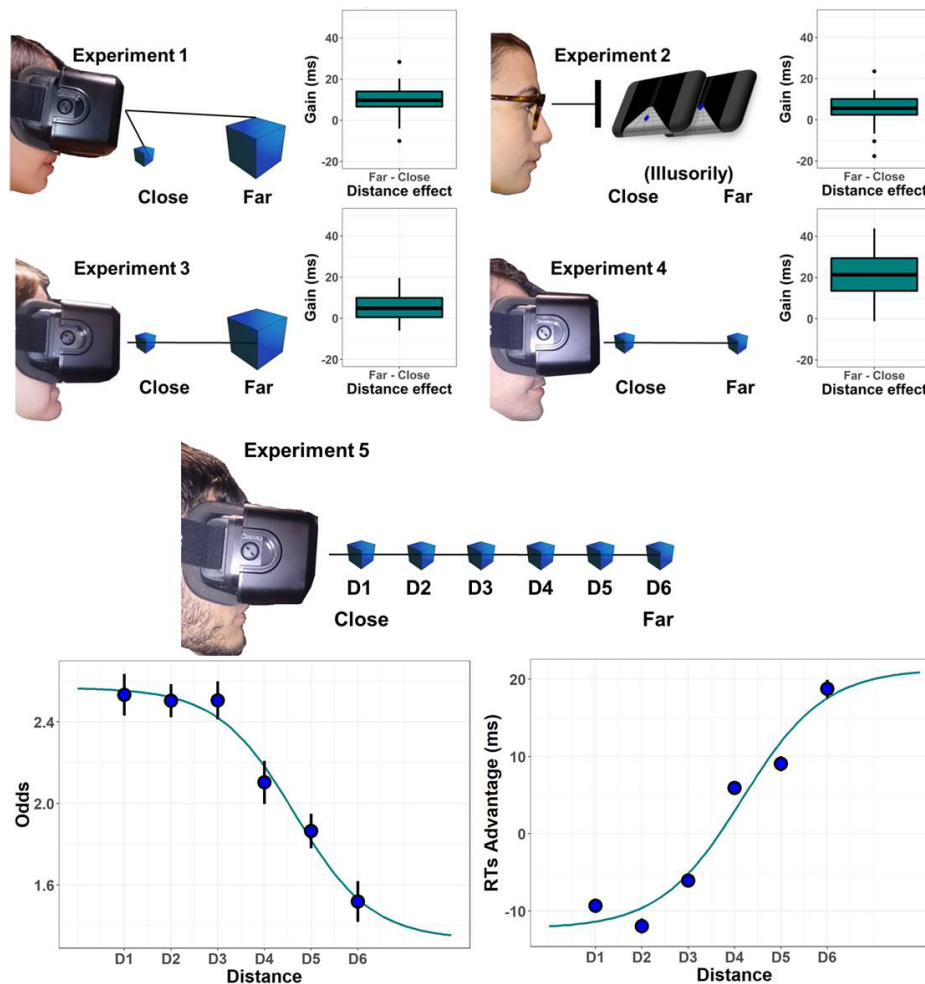
268 Purely visual advantages occurring in PPS, in contrast to multisensory ones, have been seldom reported  
269 (for a recent review, see de Vignemont, 2018), or have been framed in attentional terms (see paragraph  
270 above). The aforementioned near-hand effects for target detection, for example, actually consist of  
271 purely visual advantages, which occur without direct multisensory stimulation and depend on a *static*  
272 proprioceptive feedback. Notwithstanding the difficulty in disentangling attentional and perceptual  
273 processing (but see Makin et al, 2009; Reed et al., 2013), a recent study attempted to investigate how  
274 shape perception – classically considered a function of the ventral visual pathway (Goodale & Milner,  
275 1992) – is affected by proximity (Blini et al., 2018).

276 Blini et al. (2018) presented, to healthy participants, 3D shapes in the context of an immersive virtual  
277 reality environment (Figure 1). The geometrical shapes were presented either close (50 cm) or far (300  
278 cm) from participants, thus within reach (in PPS) or not; the task consisted in a speeded discrimination  
279 of the presented shape (i.e. cube or sphere). As physical size scales, in everyday life, with depth (that is,  
280 farther shapes appear smaller), and this has arguably a profound impact on visual capacities (experiment  
281 4), retinal size correction was applied. By equating the retinal size of close and far shapes, the latter  
282 appear illusorily bigger (because depth cues are accounted for by the visual system to estimate objects'  
283 size). Despite this striking visual illusion, participants were consistently faster in discriminating shapes  
284 appearing close to them (experiment 1, see Figure 1). Moreover, as described below, this effect could  
285 not be explained by upper/lower visual field confounds (i.e. in everyday life close objects more  
286 commonly appear at the bottom of the visual field, which could therefore be privileged, Previc, 1990),  
287 or vergence eye-movements. First, the effect persisted when both shapes appeared at the same height,  
288 that of fixation, to avoid any upper/lower visual field confound (experiment 3). Second, the effect  
289 persisted when the authors exploited a mere illusion of depth to avoid any vergence eye-movements  
290 confound (i.e. Ponzo illusion, experiment 2). In the illusion, perspective cues (i.e. converging lines) are  
291 used as a background for two elements displayed at different heights, one of which appears therefore  
292 illusorily farther away in space; thus, this context stripped the task of many important depth indices,  
293 including vergence eye-movements, except for perspective cues. Interestingly, when Blini et al. (2018)  
294 probed the spatial distribution of this performance benefit, termed distance effect, by presenting shapes  
295 at 6 equi-spaced distances from the participants, they found that a sigmoid trend could adequately  
296 account for behavioural performances in terms of both accuracy and response times. As discussed in the  
297 first paragraph, the sigmoidal trend has been considered a hallmark signature of PPS (multisensory)  
298 processing. Having described such pattern for a purely unisensory (visual) task has one important  
299 theoretical implication: defining PPS as the region of space in which multisensory interaction occurs,  
300 and explain PPS-related performance benefits in terms of multisensory convergence, is probably  
301 limiting, as it does not properly account for what appears to be a more fundamental role of PPS circuitry  
302 in perception. Researchers conducting multisensory studies should not neglect, thus, the fact that

303 unimodal stimulations alone (at least in the visual modality) could capture behavioral signatures of PPS  
304 processing, and be cautious before ascribing them to multisensory convergence.

305

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307

308

309 **Figure 1.** In the study of Blini et al. (2018), the authors sought to assess perceptual discrimination  
310 abilities across different depths. Geometrical shapes were presented close (50 cm) or far (300 cm) from  
311 participants, in a 3D virtual environment (VE) or in the context of a visual illusion of depth (experiment  
312 2); in this context, participants saw 2D images depicting perspective cues which created an illusory  
313 perception of depth. In experiments 1 (3D VE) and 2 (2D Ponzolike illusion), closer shapes appeared  
314 in the bottom part of the participants' visual field (below a fixation cross), farther ones in the upper  
315 visual field; in experiments 3, 4, and 5, all shapes were presented at the same height of the fixation cross.  
316 In experiments 1, 2, and 3, retinal size was kept constant for close and far stimuli, whereas in  
317 experiments 4 and 5 it was naturally scaled with distance. The authors consistently found an advantage

318 in discriminating shapes when these were presented close as compared to far – difference depicted in  
319 the boxplots. Furthermore, a sigmoid trend could capture the spatial distribution of this, purely unimodal,  
320 advantage (experiment 5). Image adapted from Fig. 2 and 3 in Blini et al. (2018), with permission from  
321 the authors.

322

## 323 **5. Close is better**

324 Recent proposals have questioned the view of PPS as a unitary construct, but rather declined several  
325 peripersonal space(s) according to their functional role (i.e. body protection vs. goal-directed action),  
326 and therefore sensory and motor requirements (de Vignemont & Iannetti, 2015). The lowest common  
327 denominators of these PPS constructs appear, however, to encompass two elements: the body – which,  
328 by definition, is involved in any action towards an object or defensive behavior – and the distance of a  
329 stimulus from it (i.e. proximity, in its parametric and continuous meaning). Recent frameworks have  
330 also stressed the task-dependent nature of PPS signatures, depending on “the behavioral relevance of  
331 actions aiming to create or avoid contact between objects and the body” (Bufacchi & Iannetti, 2018).  
332 The latter definition can account for the manifold variables tapping onto PPS plasticity. The magnitude  
333 of PPS functional measurements would additionally vary according to several factors, listed under the  
334 umbrella concept of behavioral relevance – and, again, hardly distinguishable from enhanced attentional  
335 processing. However, proximity to the body by itself attributes saliency to a cue (Spaccasassi, Romano,  
336 & Maravita, 2019). Interestingly, behavioral sensitivity to reward decreases in the far space (O’Connor,  
337 Meade, Carter, Rossiter, & Hester, 2014) as if the intrinsic or learned value of stimuli presented close  
338 to the body is automatically increased and gains in salience (Spaccasassi et al., 2019).

339 One could therefore put forward the general prediction that *everything* would be enhanced when close  
340 to the body, as long as the task at hand offers sufficient sensitivity and it is, indeed, enhanced by  
341 increased attentional or PPS-specific processing. The latter two requirements are not trivial. First,  
342 behavioral effects can often reveal themselves as being very fragile and necessitating of well-powered  
343 and rigorous designs (Dosso & Kingstone, 2018, for the near-hand effects). Second, one may debate  
344 whether the increased attentional salience of body parts invariantly leads to improved behavioral  
345 performance in one task. There are, indeed, instances in which hands proximity seems to *hamper* the  
346 task “at hand”. Abrams et al. (2008), for example, reported that people shifted their attention between  
347 items more slowly when their hands were near the display with respect to when their hands were placed  
348 farther apart. At odds with most previous near-hand effect studies, here both hands served as spatial  
349 attentional wands, thus possibly increasing the cost of shifting attention by modulating either the  
350 engagement or disengagement attentional components. Leveraging a classic inhibition of return  
351 paradigm, the same study indeed associated hands proximity to delayed attentional disengagement for  
352 cued locations (also see Qi, Wang, He, & Du, 2019). This can actually reflect a more thorough visual

353 assessment of the region of space around the hands (i.e. visual enhancement, not hampering), which was  
354 supported by higher accuracy in target discrimination in the visual search task when hands were near to,  
355 as compared to far from the display. There are, indeed, situations in which a more thorough assessment  
356 of the space around the hands or the body is critical, i.e. when goal-oriented actions (including  
357 reactive/defensive ones) must be performed. In this case, sensory processing of objects presented in PPS  
358 may be effectively enhanced for the sake of guiding the motor system toward an optimal response (e.g.  
359 de Vignemont, 2018). Thus, this can be reconciled with views that stress the need of a purpose to serve  
360 for PPS in order to effectively enhance performance within PPS. In this chapter we have focused on  
361 visual advantages, although such advantages may potentially extend to other modalities (e.g. audition,  
362 see Brungart, 1999; Brungart, Durlach, & Rabinowitz, 1999), or other dimensions of stimuli such as  
363 their perceived duration (Qi et al, 2019), provided the aforementioned conditions are met; more research  
364 is needed in this regard.

365 The system for PPS coding is ancient and subtended by a large neural network, already optimized for  
366 monitoring the space close to the body, as well as the distance of stimuli from it. Two scenarios are  
367 possible, and not mutually exclusive: the PPS-specific system may easily be exploited by domain-  
368 general mechanisms for saliency attribution, i.e. spatial attention, to promote the processing of relevant  
369 stimuli; the specialized PPS processing may bias spatial attention toward the region of space for which  
370 it excels. At any rate, as reviewed above, the role of PPS-processing extends, as a consequence, from  
371 multisensory interaction to more basic features of (unisensory) perception, including visual shape  
372 discrimination. Its contribution appears therefore much broader than what previously thought. In  
373 essence, while facing a potentially annoying insect, there may be no need to surrender to a  
374 speed/accuracy trade-off in visual discrimination as a function of depth: PPS-specialized processing  
375 could provide performance benefits for both processes (fast reaction and proper identification of the  
376 threat) concurrently. For a defensive system to work efficiently, i.e. by being quick without bugging  
377 constantly for stimuli not deserving protection from, such an extra perceptual boost appears indeed very  
378 convenient (Makin et al., 2015, 2009).

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## 382 **References**

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