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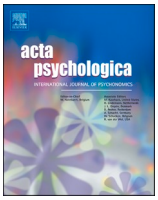

Time and numerosity estimation in peripersonal and extrapersonal space

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ABSTRACT

The representation of space, time and number is believed to rely on a common encoding system developed to support action guidance. While the ecological advantage of such a shared system is evident when objects are located within the region of space we can act on (known as peri-personal space), it is less obvious in the case of objects located beyond our arms' reach. In the current study we investigated whether and to what extent the distance of the stimuli from the observer affects the perception of duration and numerosity. We first replicated Anelli et al.'s (2015) experiment by asking adult participants to perform a duration reproduction task with stimuli of different sizes displayed in the peri- or extra-personal space, and then applied the same paradigm to a non-symbolic numerosity estimation task. Results show that, independently of size, duration estimates were overestimated when visual stimuli were presented in the extra-personal space, replicating previous findings. A similar effect was also found for numerosity perception, however overestimation for far stimuli was much smaller in magnitude and was accounted by the difference in perceived size between stimuli presented in peripersonal or extrapersonal space. Overall, these results suggest that, while the processing of temporal information is robustly affected by the position of the stimuli in either the peri- or extra-personal space, numerosity perception is independent from stimulus distance. We speculate that, while time and numerosity may be encoded by a shared system in the peri-personal space (to optimize action execution), different and partially independent mechanisms may underlie the representation of time and numerosity in extra-personal space. Furthermore, these results suggest that investigating magnitude perception across spatial planes (where it is or is not possible to act) may unveil processing differences that would otherwise pass unnoticed.

1. Introduction

A precise and reliable representation of space is crucial to efficiently interact with objects in the environment. For instance, to successfully detect, reach and grasp objects located close to us a detailed internal representation of the objects' position relative to the observer is needed. The space around us can be divided into two categories: peri-personal (PPS) and extra-personal (EPS) space, depending on the relative distance between the agent's body and the object of interest. The border between these two categories has been defined as the space within or outside our arms' reach (Rizzolatti et al., 1981) or the possible operational space of behavioral relevance achievable through tool use (Anelli et al., 2015; Canzoneri et al., 2013; Longo & Lourenco, 2006; for a review see: Hunley & Lourenco, 2018).

Previous studies have shown that spatial attention can be differently distributed when individuals operate within versus beyond PPS. For example, when asked to bisect a horizontal line, neurologically healthy individuals tend to provide leftward biased responses, a phenomenon called pseudoneglect, and thought to show a default leftward bias in spatial attention (McCourt & Jewell, 1999). Interestingly, this attentional bias attenuates progressively with distance: when asked to perform the bisection task in EPS, subjects' responses shift rightward not leftward (Longo & Lourenco, 2010; McCourt & Garlinghouse, 2000). The difference between PPS and EPS has been found to influence attention in the physical space as well as the mental representation of numbers as shown by the reduction of the leftward biases in EPS space in a mental number line bisection task involving digits (Longo & Lourenco, 2010).

The existence of multiple representations of space has also been suggested by neuroimaging studies showing that areas of the dorsal and the ventral stream were differentially recruited when stimuli were presented in either PPS or EPS (Fink et al., 2000; Weiss, 2000). A stronger

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activity in occipito-parietal regions was observed when line bisection tasks were performed in PPS compared to EPS, while the opposite contrast induced a higher activation in occipito-temporal regions (Weiss, 2000). The existence of a different neural substrate supporting the representations of PPS and EPS is further suggested by reports of a double dissociation in neglect patients, with some of them showing selective attentional deficits in PPS and others showing it only in EPS (Aimola et al., 2012; Butler et al., 2004; Cowey et al., 1994). In healthy individuals the double dissociation observed in neglect patients has been simulated by interfering with the activity of the dorsal or ventral areas via rTMS stimulation (Bjoertomt, 2002; Bjoertomt et al., 2009; Fierro et al., 2000). These results suggest a possible segregation of the cortical areas recruited when visual stimuli are processed at different distances from the observer: while perceiving stimuli in PPS potentially involves dorsal visuomotor areas, the processing of stimuli in EPS would mostly require the activation of visuo-perceptual ventral regions.

The representation of spatial information might not only be modulated by space-related characteristics of the objects but also by their temporal properties and numerosity. According to the ATOM theory, space, time and number are part of a generalized magnitude system and are processed by common neural resources (Bueti & Walsh, 2009; Walsh, 2003). Several behavioral studies showing interactions across the different magnitudes strongly support this idea of a shared representation. Duration discrimination judgments, for instance, can be influenced by the stimulus numerosity (Xuan et al., 2007), spatial position (Vicario et al., 2008) and items size (Xuan et al., 2007). Similarly, perception of non-symbolic numerosity is prone to the SNARC effect, resulting in faster reaction times to smaller numbers when responding using the left hand and vice versa, an effect suggesting an internal representation of numerosity along a spatial configuration from left to right (Dehaene et al., 1993; Nemeh et al., 2018). Numerosity perception is also influenced by other spatial non-numerical magnitudes such as total area, convex-hull, density and contour length as shown by both estimation and discrimination tasks (Dakin et al., 2011; DeWind et al., 2015; Gebuis & Reynvoet, 2012; Hurewitz et al., 2006; Nys & Content, 2012; Szucs et al., 2013) especially when these non-numerical dimensions are more salient than the numerical information.

It is worth noting that while most of the studies mentioned above reported cross dimensional interactions in PPS, it is still an open question whether these also occur in EPS. Indeed, while a shared representation of magnitudes might be useful in PPS to optimize motor routines towards objects we want to interact with, the same might not hold when these are placed out of reach. Recent reports support the idea of a different processing for temporal (duration) information when stimuli are presented in PPS or EPS (Anelli et al., 2015). Duration estimates were found to vary according to stimulus distance from the observer. When participants were asked to reproduce half of the duration of a visual stimulus (a duration bisection task) they showed a tendency to overestimate visual stimuli duration in the EPS while the opposite, underestimation, occurred for stimuli presented in the PPS (Anelli et al., 2015). The representation of Arabic numbers was also found to be affected by the position of the stimuli either in PPS or EPS: when subjects were asked to estimate the number in between two digits presented in PPS, they showed a leftward bias on their mental numberline that decreased with increasing distance between the subjects and the visual stimuli (Longo & Lourenco, 2010).

In the present study we investigated whether, similarly to duration, numerosity perception is also affected by the position of the stimuli in PPS or EPS. First we aimed at replicating the effect of viewing distance on duration perception which has been previously reported by Anelli et al. (2015). Then we tested if and to what extent the same effect also applies to numerosity perception.

2. Methods

2.1. Subjects

To establish the sample size needed to achieve an effect size comparable ($f = 0.87$) as computed from Anelli et al. (2015), we performed an a-priori power analysis. The power-analysis for a repeated-measures within factors ANOVA to evaluate the factor "stimulus distance" ($\alpha = 0.01$) revealed that 10 participants were needed to reach a power ($1\text{-}\beta$) of 0.95.

A total of 25 adults (mean age = 26.4 ± 4.03 years old, 14 females), all with normal or corrected-to-normal vision, participated in the experiments. 21 subjects were included in the duration reproduction experiment and 22 subjects in the numerosity estimation experiment (19 subjects completed both experiments). All participants gave written informed consent. The experimental procedures were approved by the local ethics committee (Comitato Etico Pediatrico Regionale – Azienda Ospedaliero-Universitaria Meyer – Firenze FI).

2.2. Stimuli and apparatus

Stimuli were created with Psychophysics toolbox for Matlab (Brainard, 1997) and displayed on a 75 Hz – 22″ LCD monitor (ASUS VW225) with a resolution of 1680 × 1050 pixels (px). Subjects were tested in a quiet dark room, to minimize visual and auditory feedback.

2.3. General procedures

We measured subjects' accuracy and precision in a duration reproduction and numerosity estimation task via a bisection paradigm. For the duration reproduction task, we replicated Anelli et al.'s (2015) paradigm: participants were asked to press the spacebar to reproduce half of the duration of a visual stimulus they were presented with. A similar paradigm was used in the numerosity task: participants were asked to verbally report half of the numerosity of the cloud of dots. In separate sessions, visual stimuli were presented in PPS or in EPS for both experiments. Subjects were allowed to take a brief break in between the two sessions. The order of sessions within each experiment was pseudo-randomized across all subjects, except for an additional control condition of the numerosity experiment that was always performed on a separate day for all subjects.

2.4. Duration reproduction task: replication of Anelli et al. (2015)

Participants sat in front of the monitor, with their dominant hand on the spacebar. During the "duration encoding phase" a blue square was centrally presented on a black background for 1600, 1800, 2000, 2200 or 2400 ms. Subsequently, after an ISI of 500 ms, a red square appeared to prompt the duration reproduction phase in which participants had to press the spacebar to reproduce half of the duration of the blue square. The red square disappeared as the spacebar was released and, after a fixed interval of 2000 ms, the next trial started (Fig. 1A). No feedback was provided to the subjects about the accuracy of their responses. In separate sessions, duration reproduction was measured with stimuli displayed at two distances from the observer: 60 cm (PPS) or 120 cm (EPS). The physical size of the stimuli was also manipulated so that there were two classes of stimuli, "small" and "big", subtending the same angular size for each viewing distance. When stimuli were presented at the nearest distance (PPS), the sizes of the small and big stimuli were 31 and 62 px respectively. When presented at the farthest distance (EPS) the sizes of the small and big stimuli were doubled relative to those presented in PPS: 62 and 124 px. As a result, small stimuli subtended 1° while big stimuli 2° (Fig. 1B) when displayed in PPS as well as in EPS. Within each session, defined by a given stimulus distance (PPS or EPS), stimuli of different sizes (small or big) were randomly presented and participants completed a single block of 60 trials (12 trials for each

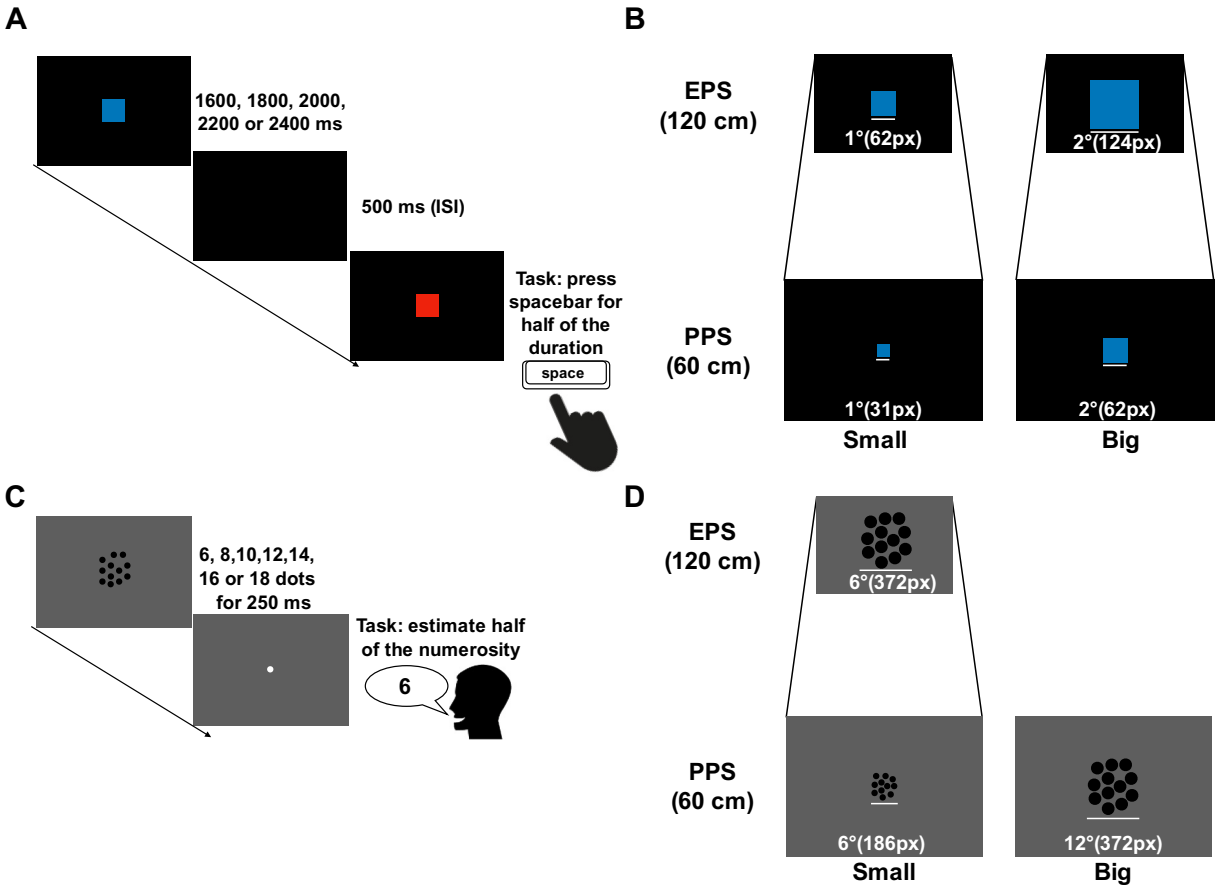

Fig. 1. Overview of the experimental design.
A. Duration Reproduction Task, replication of Anelli et al. (2015). Subjects were presented with a blue square lasting 1600, 1800, 2000, 2200 or 2400 ms. After a 500 ms ISI a red square appeared, and participants were asked to press the spacebar for half of the duration of the blue square. The red square disappeared when the spacebar was released and the next trial started.
B. Example of stimuli used in A. Stimuli could be either small (1°) or big (2°) and the screen was placed at either 60 cm (PPS) or 120 cm (EPS) from the subject. Stimuli presented in PPS were retinotopically matched to those presented in EPS (small/big stimuli subtended 1°/2° corresponding to a size of 31/62 and 62/124 px in PPS and EPS respectively).
C. Number Estimation Task. Subjects were briefly (250 ms) presented with a cloud of dots consisting in 6, 8, 10, 12, 14, 16 or 18 dots. Subsequently, a white dot appeared in the center of the screen and subjects were asked to verbally estimate half of the numerosity shown in the array. An experimenter (blind to the stimuli) stopped the registration time when the participant gave the number and recorded the answer via keypress.
D. Example of stimuli used in C. Stimuli could be either small (6°) or big (12°) and the screen was placed at either 60 cm (PPS) or 120 cm (EPS) from the subject. Small stimuli shown in PPS were retinotopically matched to the ones shown in EPS (6°) corresponding to 93 and 186 px respectively. In the control condition big stimuli were presented in PPS and subtended 12° (372 px). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

duration).

2.5. Number estimation task

Participants were briefly (250 ms) presented with a central cloud of 6, 8, 10, 12, 14, 16 or 18 black dots. Participants were asked to verbally report half of the numerosity of the cloud as fast as possible (Fig. 2C). An experimenter, blind to the stimuli, stopped the reaction time recording as soon as the answer was given by the subject and recorded the answer via a keypress. Subjects were informed about the range of numerosity tested, but they were not given any feedback about the accuracy of their estimates neither during nor at the end of the experiment. As for the duration experiment, the task was performed twice, once with the monitor placed in PPS and once in EPS (60 and 120 cm respectively).

Each dot in the cloud subtended 0.4° and the dots spatial configuration was designed to have them fall within a virtual circle of 6° diameter in both PPS and EPS conditions (i.e. the angular size of the stimuli was the same irrespective of stimuli distance). This implied that the diameter of individual dots was either 12 or 24 px and the size of the virtual circles was either 186 or 372 pixels for stimuli presented in PPS and EPS respectively (Fig. 2D). For each spatial condition a total of 140 trials were tested divided into 5 blocks of 28 trials each, separated by breaks. This procedure ensured that each numerosity was tested 20 times at each distance.

An additional condition was devised to control for possible interactions between numerosity estimates and stimulus size (Dakin et al., 2011; DeWind et al., 2015; Gebuis & Reynvoet, 2012; Hurewitz et al., 2006; Nys & Content, 2012; Szucs et al., 2013) consisting of a numerosity estimation task performed with stimuli subtending 12° (372 pixels) with the diameter of individual dots equal to 0.8° (24 pixels) displayed in PPS. In this condition subjects collected 140 trials divided into 5 blocks.

2.6. Statistical analysis

For each task (duration or numerosity) we measured the perceived magnitude and the precision of the responses separately for each participant. Perceived magnitude was indexed as the median of subjects'

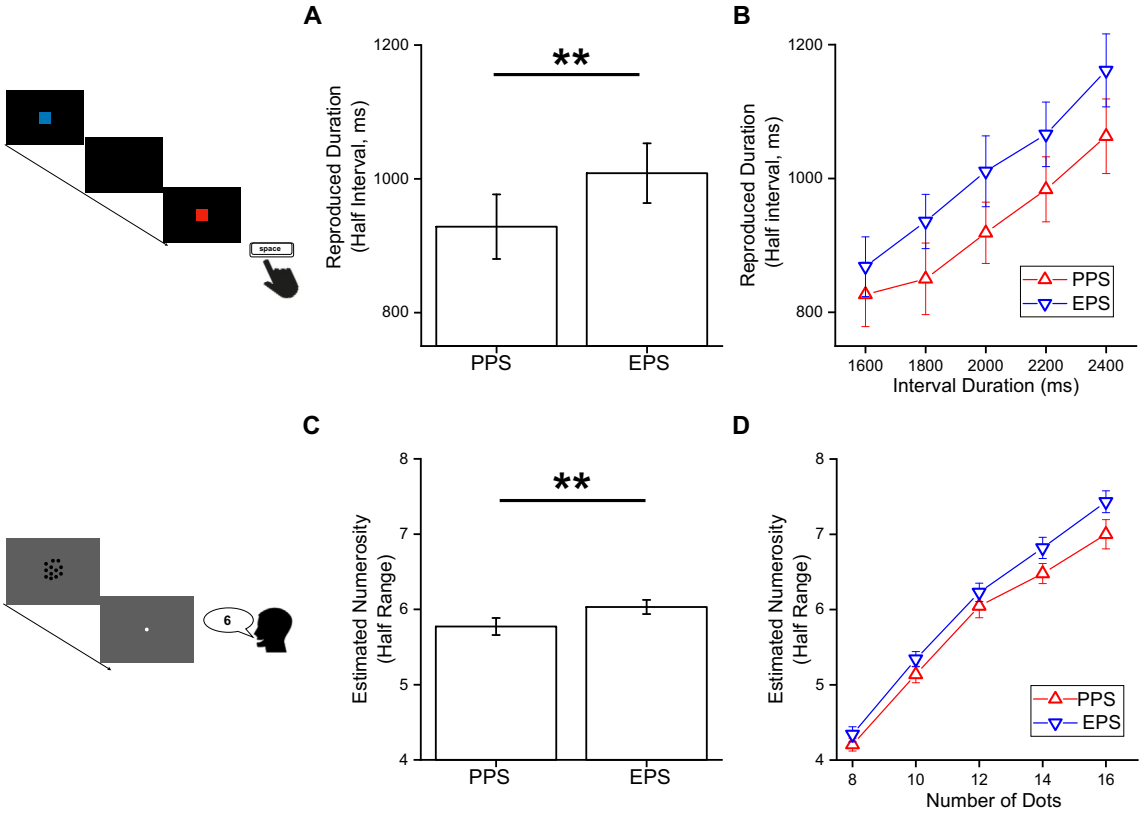

Fig. 2. Perceived duration and numerosity in peripersonal vs extrapersonal space.
A. Perceived duration in peri-personal vs extra-personal space. On average subjects significantly overestimated duration when stimuli were presented in EPS than PPS. Bars depict mean [M] ± 1 standard error of the mean [SEM]. $^{**}p < 0.01$.
B. Perceived duration plotted as a function of the veridical duration (y and x axis respectively) for stimuli presented in PPS (red) and EPS (blue). All tested durations were reproduced as lasting longer when stimuli were presented in EPS compared to PPS. Symbols represent average across subjects ($N = 21$, data points show M ± SEM). $^{**}p < 0.01$.
C. Perceived numerosity in PPS vs EPS space. Subjects significantly overestimated numerosity when stimuli were presented in EPS.
D. Perceived numerosity plotted as a function of the veridical numerosity (y and x axis respectively) for stimuli presented in PPS (red) and EPS (blue). All tested numerosities were estimated as more numerous when stimuli were presented in the EPS compared to PPS ($N = 22$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

responses, while precision was indexed by Weber fractions, that is, the standard deviation on the response distribution for a given stimulus magnitude, normalized by the mean response for the same magnitude. In order to control for outliers, responses were also converted into Z scores and those lower or higher than 3 were excluded from the analysis (as a result less than 1% of all trials across all subjects and conditions for the numerosity task were discarded while no trials were discarded in the duration task). To assess whether, and to what extent, differences in stimulus size (a dimension that covaries with distance when the object angular size is kept fixed) play a role in duration and numerosity estimates, we compared the perceived magnitude for small stimuli in PPS (small PPS) with the perceived magnitude for big stimuli in PPS (big PPS) and with the small stimuli in EPS (small EPS). The difference in perceived magnitude was quantified using the following equation:

$$Difference = \left(\left(\frac{Perceived\ Magnitude_{BigPPS\ or\ SmallEPS}}{Perceived\ Magnitude_{SmallPPS}}\right) - 1\right) * 100$$

Statistical significance for differences in accuracy and precision of the achieved estimates in both PPS and EPS were analyzed by repeated measures ANOVAs (when Mauchly's Test of Sphericity was significant the Greenhouse-Geisser correction was applied), ANCOVAs and post-hoc paired *t*-tests. Statistical analyses were performed with SPSS Software (IBM Corp. Released 2019. IBM SPSS Statistics for Macintosh, Version 26.0. Armonk, NY: IBM Corp.) while the power analysis was performed using G*Power software (version 3.1.9.3 for Macintosh) (Faul et al., 2007).

3. Results

3.1. Perceived duration and numerosity in peripersonal and extrapersonal space

3.1.1. Duration reproduction task: replication of Anelli et al.'s (2015)

For the duration reproduction task we replicated the experiment previously performed by Anelli et al. (2015). Fig. 2A shows how duration estimation differs in PPS and EPS: on average, reproduced durations were significantly overestimated when stimuli were displayed in the EPS compared to the PPS by about 80 ms (mean value ± S.E.M. for EPS: 1008 ± 45 ms and for PPS: 928 ± 49), a result in line with Anelli et al. (2015). To assess whether this effect occurred for each of the tested stimulus durations, we plotted participants' responses as a function of the veridical duration for stimuli in PPS (red) and EPS (blue) for each tested duration (Fig. 2B). All tested durations were reproduced as longer when stimuli were displayed in EPS compared to PPS. To test for the statistical significance of these differences, subjects' reproduced durations were entered in a Two-Way Repeated Measures ANOVA with "stimulus distance" (2 levels: PPS or EPS) and "duration" (5 levels, 1600, 1800, 2000, 2200 or 2400 ms) as factors. The ANOVA revealed a main effect of duration, meaning that the subjects correctly performed the task by varying their estimates of the different interval's length (F

(1.95,39.06) = 49.8, η^2_p = 0.71, $p < 0.001$), post-hoc analyses confirmed that all the durations estimated were indeed statistically different from each other (all p-values < 0.05). Importantly, the perceived duration was significantly overestimated for stimuli in PPS (1008 ± 45 ms) compared to stimuli in EPS (928 ± 49) (significant main effect of the "stimulus distance" factor: ($F(1,20) = 12.67$, $\eta^2_p = 0.39$, $p = 0.002$)). The overestimation effect was comparable across all tested durations, as shown by the non-significant interaction between duration and space ($F(2.54,50.74) = 0.94$, $\eta^2_p = 0.05$, $p = 0.42$).

To summarize, the duration estimation task succeeded in replicating the previous report by Anelli et al. (2015) and with a similar effect size ($\eta^2_p = 0.43$ vs. $\eta^2_p = 0.39$) showing that duration of visual stimuli is perceived differently in PPS and EPS, with stimuli shown in EPS space being estimated as lasting longer compared to those presented in PPS.

3.1.2. Numerosity estimation task

Once the robustness of the paradigm used by Anelli et al. (2015) was confirmed for the investigation of visual duration perception in PPS and EPS, we applied a very similar paradigm to the perception of visual numerosity. Instead of reproducing half of the duration of a stimulus, in this task subjects were asked to verbally report half of the perceived numerosity of a quickly presented set of elements (preventing serial counting). As participants were informed about the tested numerical range, they could have anchored their response to the two extreme numerosity and this, in turn, could have provided edge effects. To control for this possibility, we discarded the two extreme numerosities (6 and 18 dots) from all the analyses (see Fig. 2C). The results (Fig. 2C) indicate that subjects showed a slight tendency to overestimate the numerosity of stimuli presented in EPS compared to PPS: averaged estimates pooled across all numerosities were equal to 6.03 ± 0.10 and 5.77 ± 0.12 (mean value ± S.E.M.) for stimuli presented in the EPS or PPS space respectively. Similarly to the duration experiment, we analyzed participants' responses as a function of the veridical numerosity in PPS and EPS separately for each tested numerosity. Numerosity estimates were entered in a Two-Way Repeated Measure ANOVA with "stimulus distance" (PPS or EPS) and numerosity (8, 10, 12, 14 or 16 dots) as factors. The main effect of numerosity was significant ($F(2.25,47.29) = 284.48$, $\eta^2_p = 0.93$, $p < 0.001$) meaning that subjects correctly performed the task by modulating their estimates of the different numerosities, as confirmed by post-hoc tests (all p-values < 0.05). Most importantly, there was an overall tendency to overestimate numerosity in EPS compared to PPS, as indicated by a significant main effect of the factor "stimulus distance" ($F(1,21) = 11.69$, $\eta^2_p = 0.36$, $p = 0.003$). The interaction between numerosity and space was not statistically significant ($F(3.03,63.54) = 1.05$, $\eta^2_p = 0.05$, $p = 0.38$), suggesting that perceptual biases were similar across numerosities.

3.2. Influence of stimulus size on perceived duration and numerosity

In both experiments about perceived duration and numerosity, stimuli in the EPS were retinotopically matched to those presented in PPS. This means that while the stimuli were subtending the same angular size (at the level of the retina) they were physically different and potentially perceived to be so (larger stimuli in EPS). This is a realistic hypothesis because several depth cues were available to participants (e.g. the screen frame and the table edges). Moreover, previous studies have found interactions between size and both numerosity and temporal perception, with larger visual stimuli perceived as lasting longer (Rammsayer & Verner, 2014; Xuan et al., 2007) and being more numerous (Dakin et al., 2011; DeWind et al., 2015; Gebuis & Reynvoet, 2012; Hurewitz et al., 2006; Nys & Content, 2012; Szucs et al., 2013) compared to smaller stimuli. To rule out the possibility that the change in perceived duration and numerosity for stimuli presented in the EPS was driven by stimulus size and not by their distance, we compared subjects' responses to small stimuli in PPS and EPS (having the same angular size) with those obtained in a condition in which large stimuli were presented in PPS. If perceived magnitude is affected by stimulus distance regardless of stimulus size, we expected to find differences in subjects' responses for stimuli presented in PPS and EPS (small stimuli in PPS vs. small stimuli in EPS) but not when stimuli of different sizes were presented at the same distance (big stimuli in PPS vs. small stimuli in PPS). On the other hand, if stimulus size plays a role in defining perceived duration and numerosity, we should find a difference between estimating stimuli of different sizes presented at the same distance (big stimuli in PPS vs. small stimuli in PPS). First, we compared subjects' responses in the small stimuli condition in PPS and EPS (i.e. stimuli that were matched for angular size but differed in physical size), after covarying out the responses provided in the condition with big stimuli displayed in PPS (i.e. stimuli that had the same physical size of small stimuli in EPS). For the duration experiment, we performed an RM ANCOVA entering the perceived duration for the small stimuli in PPS and small stimuli in EPS conditions as dependent variables with "stimulus distance" (2 levels: PPS or EPS) and "duration" (5 levels: 1600, 1800, 2000, 2200 or 2400 ms) as factors and the perceived duration for the big stimuli in PPS condition as a covariate. The main effect of stimulus distance remained significant for duration estimates ($F(1,15) = 8.93$, $\eta^2_p = 0.37$, $p = 0.009$), demonstrating that perceived duration was genuinely overestimated for stimuli presented in the EPS relative to those presented in the PPS, a result again in line with that found by Anelli et al. (2015). The same analysis was performed for perceived numerosity. In this case results showed that the difference in perceived numerosity for stimuli of the same angular size presented in PPS or EPS space (small stimuli in PPS and small stimuli in EPS) was not statistically significant ($F(1,16) = 1.32$, $\eta^2_p = 0.08$, $p = 0.27$) when the difference in physical size was taken into account (responses for big stimuli in PPS stimuli used as covariate), suggesting that the size of the stimuli and not their distance in space accounted for the perceptual illusion reported in the numerosity estimation experiment.

The possible role of perceived size relative to stimulus distance was further investigated by comparing responses to big stimuli in PPS and to small stimuli in EPS (stimuli in both conditions have the same physical size) against the condition with small stimuli in PPS (stimuli used as baseline) that matched the former for stimulus distance and the latter for stimulus angular size. The difference was quantified by using the equation illustrated in the Statistical Analyses paragraph of the Methods section. Again, if responses were modulated by stimulus distance and not by stimulus physical size, the difference in subjects' responses was expected to be zero when comparing stimuli of different physical size shown at the same distance from the observer (small stimuli in PPS vs. big stimuli in PPS). On the other hand, a statistically significant difference in subject's responses had to be expected when comparing stimuli of the same angular size (even if different in physical size) shown at different distances (small stimuli in PPS vs. small stimuli in EPS). The results showing the effect of distance on perceived duration are reported in Fig. 3A, where we plotted the mean effect averaged across all durations/numerosities and across subjects. An almost null (0.11% ± 1.45) difference was obtained when comparing perceived duration for stimuli of different sizes presented at the same distance (small stimuli in PPS vs. big stimuli in PPS), which indicates that difference in physical size did not affect subjects' duration estimates. On the other hand, when comparing durations estimates of stimuli that differed for both, in physical size and distance (small stimuli in PPS vs. small stimuli in EPS) a mean difference of 9.99% ± 2.67 emerged and it was significantly larger ($t(20) = -3.38$, $p = 0.003$) than the first one (small stimuli in PPS vs. big stimuli in PPS), suggesting that distortions in duration estimates were mostly triggered by stimulus distance from the observer.

Fig. 3B shows the same analysis for the numerosity task. In this case, once normalized by the baseline (small stimuli in the PPS), perceived numerosity for stimuli of the same physical size presented in the PPS was 4.97% (±1.35) and 2.56% (±1.62) in the EPS with a not statistically significant difference ($t(21) = 1.74$, $p = 0.1$). These results suggest that perceived numerosity, at odds with duration, is primarily affected by

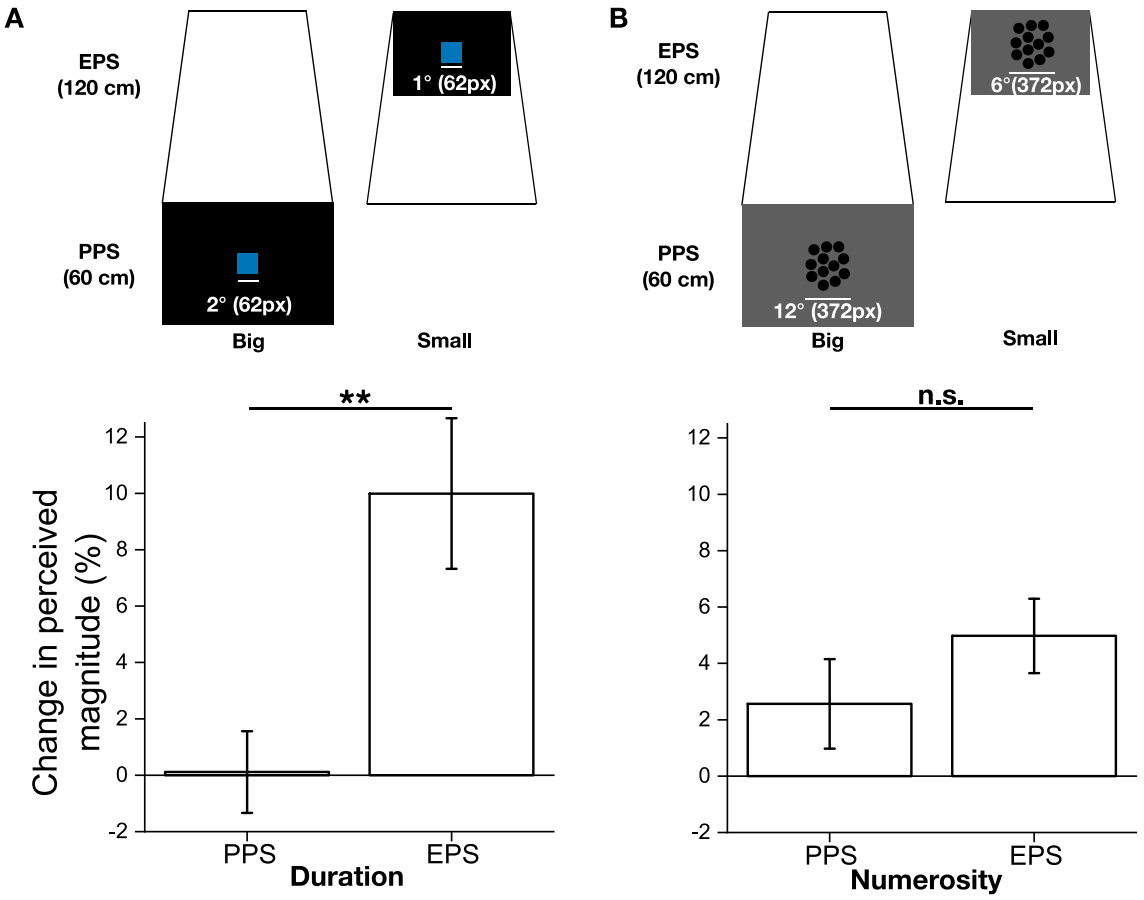

Fig. 3. Perceptual difference induced by stimulus physical size and distance on perceived duration and numerosity.
A. Changes in perceived duration for big (2°) stimuli presented in PPS and small (1°) stimuli presented in EPS relative to the baseline condition defined by small (1°) stimuli presented in the PPS. Perceived duration of the stimuli in PPS was the same despite stimuli differing in size. On the contrary, duration estimates were overestimated for stimuli presented in EPS compared to those presented PPS.
B. Changes in perceived numerosity for big (12°) stimuli presented in PPS and small (12°) stimuli presented in EPS relative to small (6°) stimuli presented in PPS. Regardless of distance from the observer, the numerosity of stimuli was always overestimated, suggesting that stimulus perceived size, not distance was the cause of the distortions in perceived numerosity.
In both panels, bars represent data averaged across subjects and error-bars indicate ±1SEM.

stimulus perceived size with such an effect accounting for the overestimation of stimulus numerosity presented at far distance (EPS).

To summarize, these analyses revealed that presenting stimuli within or beyond PPS had different effects on duration and numerosity perception. While perceived duration was genuinely modulated by stimulus distance (independently of stimulus perceived size), difference in perceived numerosity for stimuli displayed at different distances appeared to be, to a large extent, induced by the difference in stimulus size.

3.3. Perceptual precision in duration and numerosity estimation in peripersonal and extrapersonal space

One main concern with perceptual biases is that they might derive from a decrease in the subject's precision or an increase in task difficulty, rather than from a real perceptual change induced by an environmental factor, such as the distance of the stimulus from the observer (Anobile et al., 2019; Castaldi et al., 2018). To rule out this possibility we analyzed Weber fractions for each subject as this measure is commonly used to assess subject's precision. The results indicate that Wfs were overall higher for the duration than numerosity experiment ($0.20 \pm 0.01$and 0.13 ± 0.003 respectively). Importantly, Wfs were not statistically different between PPS and EPS neither in the duration task (mean value ± S.E.M. for small stimuli in PPS:0.22 ± 0.02; small stimuli in EPS: 0.19 ± 0.01, $F(1,20) = 3.11$, $p = 0.09$) nor in the numerosity task (mean value ± S.E.M. for small stimuli in PPS $= 0.14 \pm 0.004$, small stimuli in EPS: 0.13 ± 0.005, $F(1,21) = 1.41$, $p = 0.25$) suggesting that changing the stimuli distance from the observer did not significantly affect their precision. In conclusion, the effect of stimulus distance on perceived duration and numerosity was unlikely to be driven by the subject's lower perceptual precision in performing both estimation tasks but, rather, by a perceptual change induced by stimuli being presented either in the PPS or EPS.

4. Discussion

It has been recently demonstrated that duration perception of visual stimuli differs when stimuli are presented in PPS or EPS (Anelli et al., 2015). In the current study we tested whether numerosity perception is also influenced by viewing distance. Specifically, we asked whether duration and numerosity judgments are prone to similar perceptual biases when stimuli are presented in PPS or EPS. We first replicated Anelli et al.'s (2015) results, showing that duration is overestimated in EPS compared to PPS. We then devised a similar procedure to test whether numerosity judgments were also biased by stimuli distance, with stimuli presented in EPS being overestimated compared to those presented in PPS. Crucially, while the overestimation found in the duration task was genuinely induced by the stimulus distance from the

observer, in the numerosity task the effect was explained by stimulus perceived size rather than by the stimulus distance from the observer. The different effects on numerosity and duration judgments suggest that the perception of these magnitudes might rely on partially different mechanisms and highlight the importance of considering the action-space as a tool to investigate differences between magnitudes perception.

In line with the experiment by Anelli et al. (2015), we found that stimulus duration was significantly overestimated in EPS compared to PPS and that this effect was not mediated by stimulus size. The independence of duration judgments from stimulus size might seem in contrast with previous studies reporting interference effects across dimensions, e.g. larger stimuli were found to be judged as lasting longer using discrimination (Xuan et al., 2007) or full-length interval reproduction (Rammsayer & Verner, 2014) tasks. One possibility is that in the present study, the variability induced by having to reproduce only half of the presented duration might have washed out the bias induced by stimulus size. However, given that the studies reporting interference effects across dimensions used shorter stimulus duration (Rammsayer & Verner, 2014; Xuan et al., 2007), future experiments will be needed to achieve a definitive answer.

We then tested the effect of distance on numerosity perception. Mirroring what we found for duration judgments, numerosity was also overestimated when stimuli were shown in EPS compared to PPS, although to a much lesser extent (a difference of about a factor of 2). Importantly however, we demonstrated that in this case the overestimation was due to the interference between numerosity and stimulus perceived size rather than by viewing distance. In the current study, in order to match the angular size of the stimuli at different distances, stimuli shown in extrapersonal space were physically larger compared to those shown in peripersonal space. Even if stimuli were retinotopically matched, visual depth cues may have been used to cognitively infer the real size of the stimuli presented in EPS. Such cognitive strategy may have triggered overestimation of numerosity judgments due to differences in perceived stimulus size. This hypothesis was indeed confirmed: overestimation of numerosity occurred even when participants were tested with stimuli presented in PPS but larger in size. Varying stimulus size without changing the distance from the observer was sufficient to account for the overestimation effect observed when placing the (same) physically larger stimulus in EPS. This is in line with previous studies reporting interference effects between stimulus size and numerosity judgments (Dakin et al., 2011; DeWind et al., 2015; Gebuis & Reynvoet, 2012; Hurewitz et al., 2006; Nys & Content, 2012; Szucs et al., 2013).

Taken together, these results suggest that numerosity perception, at least in the numerical range tested in the current experiment, seems to be much less affected by stimulus distance which, on the other hand, genuinely affects duration estimates. Whether there is an effect of distance on numerosity ranges higher than those employed in the current experiment is currently unknown. A recent set of behavioral studies has demonstrated that at least three different systems support numerosity perception: the subitizing system for arrays of up to 4 items, the approximate number system (for numerosities higher than 4 and below the density range) and the texture/density system that kicks in for very high numerosities when segregation of the items becomes impossible (see: Anobile, Cicchini, & Burr, 2016 for a review). These three numerical regimes are governed by different psychophysical rules and rely to a different extent on attentional resources (Anobile, Tomaiuolo, et al., 2020; Castaldi et al., 2020; Pomè et al., 2019). In the current study the presented (8 to 16 items) and the estimated numerosities (i.e. the half of the displayed numerosities) were comprised within the approximate number range. Given that a signature of the approximate number system is to be characterized by constant Weber fractions, we expect the current results to hold also for slightly higher numerosities as long as they tap onto the same approximate number system. However, for even higher numerosities analyzed by the density system, the current results may not hold. Future studies should test whether the conclusion of the current study can be extended to a larger numerical range.

It can be objected that Weber fractions differed between tasks, potentially suggesting that the numerosity estimation task was slightly easier compared to the duration task. While we cannot formally rule out the possibility that the PPS/EPS effect was smaller in the numerosity task due to the lower difficulty of the numerosity compared to the duration estimation tasks, we think that this interpretation is unlikely. Indeed, within each task (numerosity and duration separately), the Weber fractions did not change between PPS and EPS, yet durations were overestimated in EPS while the same did not hold for numerosity when size was taken into account. Given that the Weber fractions were similar within each task and across spatial locations, the effect of stimulus distance on perceived duration and numerosity can hardly be explained by the subject's lower perceptual precision in performing the task in PPS compared to EPS. Thus, rather than depending on task difficulty, the perceptual change seems to be genuinely induced by stimuli being presented at two different locations in space. Nevertheless, future studies should replicate the current result after selecting stimuli that would match Weber fractions across both dimensions (numerosity and duration).

Numerical perception at different distances has been previously investigated by Longo and Lourenco (2010), however in this case a different task was used, involving symbolic rather than non-symbolic numerosities. The authors used a mental number line bisection task with symbolic numbers and found a leftward bias in PPS which tended to disappear when performed in EPS and concluded that numerical space is affected by the distance. Our results, suggesting that numerosity might not be affected by stimulus distance, seem in contradiction with this conclusion. However, beyond the major methodological differences between experiments (number bisection task with digits vs numerosity estimation), it is worth noting that the effect reported by Longo and Lourenco (2010) was most pronounced at larger distances in EPS compared to those tested in the current study and their effect was much weaker at 120 cm from the subject, which corresponds to the only distance tested here. Our results are thus in line with their observation at the same distance. Future studies should test whether increasing the viewing distance even more would result in overestimation of numerosity or whether distance has a different impact on non-symbolic and symbolic numbers.

To summarize, the current results suggest that duration and numerosity perception is differently modulated in PPS and EPS. The interaction between time, numerosity and space has been highlighted by several studies, suggesting a common encoding system shared between domains as proposed by the ATOM theory (Bueti & Walsh, 2009; Walsh, 2003; Walsh et al., 2013). For example, it has been demonstrated that adapting to duration alters numerosity discrimination judgments (Tsouli et al., 2019). Furthermore, more numerous stimuli are judged as lasting longer, compared to less numerous stimuli, and vice versa, stimuli presented for longer durations are perceived as being more numerous (Javadi & Aichelburg, 2012).

One of the key ideas of the ATOM theory is that the development of a common magnitude system may be shaped by actions. Space, time and numerosity are highly correlated in the environment and we learn this association through active interactions (Bueti & Walsh, 2009). Recent studies confirmed the idea that magnitudes perception is closely linked to the activity of the motor system (Anobile et al., 2019; Anobile, Arrighi, et al., 2020). A form of sensory adaption, called "motor adaptation", has been proven to be a useful tool to reveal visuomotor interactions (Anobile, Arrighi, et al., 2016; Maldonado Moscoso et al., 2020). When participants were asked to perform a series of finger tapping movements with their dominant hand in the same spatial location in which a visual test stimulus was subsequently presented, numerosity estimates of visual arrays or sequences of flashes and the speed of a moving grating were significantly over or underestimated depending on the tapping rate during the adaptation period (Anobile, Arrighi, et al., 2016; Anobile, Cicchini, & Burr, 2016; Anobile et al., 2019). These

results suggest a common influence of the motor system on the perception of both numerosity and duration. However, it is important to note that these studies were performed with all stimuli displayed at a short distance from the observer, within the PPS. Future studies are needed to test whether the same interactions between the motor and the perceptual system also occur when stimuli are presented in the EPS, that is out of arm's reach.

Interestingly, the ATOM theory predicts that, given that the development of a magnitude system was meant to optimize action execution, our perception of magnitudes (and the interference effects among them) may vary depending on whether the stimuli are within or outside the 'action space' (Bueti & Walsh, 2009). The current study provides empirical evidence in support of this hypothesis: perceived duration and numerosity were both overestimated for stimuli presented out of the arm's reach (EPS). However, while distortions for perceived duration were genuinely yielded by viewing distance, those for numerosity were triggered by the interaction between stimulus size and numerosity and not by viewing distance, suggesting that this parameter may not equally affect information processing in the three dimensions of the ATOM: space, time and quantity.

Overall, the present findings suggest the existence of at least partially independent systems, one for PPS, which is the one relevant for the execution of motor actions, and the other for the EPS, in which a shared processing of time and numerosity may not be so useful, as an immediate interaction with far stimuli cannot be achieved. This view is in line with the recent "Action Field Theory of Peripersonal Space" by Bufacchi and Iannetti (2018). The authors suggested a functional definition of peripersonal space defined as the space of "relevance of potential actions that aims to either create or avoid contact between a stimulus and a body part" (Bufacchi & Iannetti, 2018). Our findings suggesting that numerosity and duration may be encoded by the same system in PPS to support action guidance, but not necessarily in EPS, where goal-directed actions on the objects cannot be executed, fit well with this idea.

In conclusion, our results point to a partial dissociation in the processing of numerosity and duration that seems to be affected differently by stimulus location in either PPS or EPS. However, if the proposed dissociation between the systems supporting numerosity and duration perception were to be confirmed, it would not necessarily provide evidence against the ATOM theory. Indeed, if the link between magnitudes develops through the motor system (Anobile, Arrighi, et al., 2020), space, time and number might share the same metrics only when presented in the space we can act on, while they might be encoded differently in the space where actions are not possible. More generally, this study suggests that investigating the perception of stimulus properties as a function of distance from the observer and, in particular, comparing magnitudes perception across locations where it is or is not possible to act (EPS Vs PPS) may be a useful tool to reveal how magnitudes are represented, as some characteristics of the related mechanisms may otherwise pass unnoticed when a single spatial plane is taken into consideration.

CRediT authorship contribution statement

Irene Petrizzo: Conceptualization, Investigation, Formal Analysis, Writing – Original Draft; **Elisa Castaldi:** Conceptualization, Formal Analysis, Writing – Review & Editing; **Giovanni Anobile:** Conceptualization, Formal Analysis, Writing – Review & Editing; **Simone Bassanelli:** Conceptualization, Investigation; **Roberto Arrighi:** Conceptualization, Formal Analysis, Writing – Review & Editing.

Data Accessibility

Data accessibility. Data used in this study have been deposited on Zenodo Repository at the following link: https://zenodo.org/record/4609896#.YFmvNEhKisp.

Declaration of competing interest

None.

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