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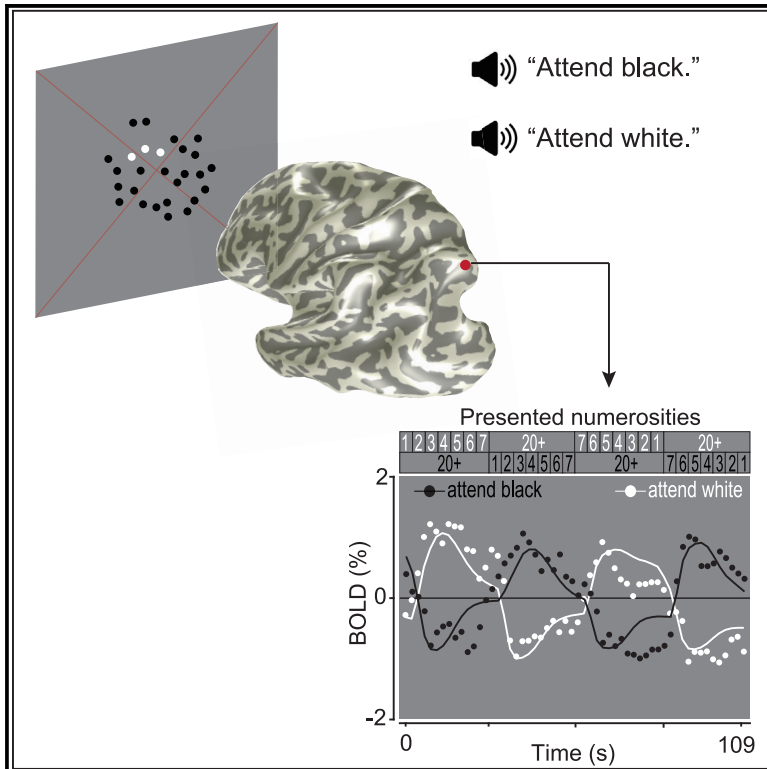
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## Attention drives human numerosity-selective responses

### Graphical abstract



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### In brief

Cai et al. investigate effects of attention on numerosity-selective neuronal populations using stimuli consisting of two dot subsets in opposite colors. Participants attended to one of the subsets. Numerosity-selective neuronal populations respond to the attended subset while suppressing responses to the non-attended subset. Attention is necessary for numerosity-selective neuronal responses.

### Highlights

- Neural populations respond selectively to numerosities, i.e., prefer numerosities
- Attention is required to elicit numerosity-selective neural responses
- Attention to the stimulus set is enough, i.e., numerosity judgement is not required
- Without attention, response to preferred numerosity is suppressed



## Report

# Attention drives human numerosity-selective responses

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## SUMMARY

Numerosity, the set size of a group of items, helps guide behavior and decisions. Previous studies have shown that neural populations respond selectively to numerosities. How numerosity is extracted from the visual scene is a longstanding debate, often contrasting low-level visual with high-level cognitive processes. Here, we investigate how attention influences numerosity-selective responses. The stimuli consisted of black and white dots within the same display. Participants' attention was focused on either black or white dots, while we systematically changed the numerosity of black, white, and total dots. Using 7 T fMRI, we show that the numerosity-tuned neural populations respond only when attention is focused on their preferred numerosity, irrespective of the unattended or total numerosities. Without attention, responses to preferred numerosity are suppressed. Unlike traditional effects of attention in the visual cortex, where attention enhances already existing responses, these results suggest that attention is required to drive numerosity-selective responses.

## INTRODUCTION

Perception of numerosity (item number) guides human and animal behavior and decisions (Brannon and Terrace, 1998; Dehaene, 2001; Nieder, 2020; Nieder and Dehaene, 2009). Neurophysiological experiments show numerosity-tuned neurons, responding maximally to a specific numerosity, with responses decreasing with distance from this preferred numerosity in crows (Ditz and Nieder, 2015; 2016a), non-human primates (Nieder and Merten, 2007; Nieder et al., 2002), and humans (Kutter et al., 2018). Functional magnetic resonance imaging (fMRI) experiments also revealed responses to numerosity tasks (Dehaene et al., 1999) and specific numerosities (Eger et al., 2009; Piazza et al., 2004). Population receptive field (pRF) modeling (Dumoulin and Wandell, 2008) shows these responses to specific numerosities reflect neural population numerosity tuning in each fMRI recording site (Harvey et al., 2013a). These neural populations are organized in a network of topographic maps, where preferred numerosity changes gradually across the cortical surface (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Hofstetter et al., 2021; Tsouli et al., 2021).

There is a longstanding debate on how numerosity is extracted from visual scenes. Some have proposed that numerosity perception follows non-numerical image features, such as area and density, that often follow numerosity (Dakin et al., 2011; Durgin, 2008; Gebuis et al., 2014). But growing psychophysical (Cicchini et al., 2016; DeWind et al., 2015), neuroimaging (DeWind

et al., 2019; Harvey and Dumoulin, 2017b, 2018; Park et al., 2016), and computational (Kim et al., 2021; Stoianov and Zorzi, 2012; Zorzi and Testolin, 2018; Nasr et al., 2019; Nasr and Nieder, 2021) evidence indicates numerosity itself is perceived and represented, akin to other visual features like color and motion (Burr and Ross, 2008). Numerosity may be estimated from early visual representations, such as spatial frequency domain image representations (Dakin et al., 2011; Paul et al., 2022), which may also underlie the similarity of numerosity to low-level visual properties like position, orientation, and spatial frequency in aspects of its perception (e.g., adaptation; Burr and Ross, 2008) and neural representation (e.g., neural tuning and topographic mapping; Tsouli et al., 2022). Although numerosity estimation may rely on low-level processes, higher level processes are clearly involved in numerosity perception, such as grouping (Maldonado Moscoso et al., 2020; Pan et al., 2021), connectedness (He et al., 2015; Kirjakovski and Matsumoto, 2016), multi-sensory integration (Anobile et al., 2016a; Nieder, 2012), working memory (Ditz and Nieder, 2016b), and attention (Anobile et al., 2013; Ansari et al., 2007; Burr et al., 2010).

Behavioral studies investigating attention's role in numerosity processing provide mixed results: it remains unclear whether and to what extent attention modulates neural responses to numerosity. Numerosity perception can appear pre-attentive, spontaneous even, when participants perform no numerosity task and their focus of attention is away from stimulus (Hesse et al., 2017). Enumerating small numbers of items (up to four,



subitizing) shows fast, error-free perception so has traditionally been seen as pre-attentive (Trick and Pylyshyn, 1993, 1994). However, attention is needed in numerosity processing, even in the subitizing range, as shown using an inattentive blindness paradigm (Railo et al., 2008). Furthermore, cross-sensory dual tasks show that subitizing and mapping numerosity onto space are attentional demanding (Anobile et al., 2012a; 2012b). Even more attentional resources are needed for subitizing than in the larger (estimation) numerosity range (Burr et al., 2010; Pomè et al., 2019).

Here, we ask how the responses of numerosity-tuned neural populations are affected by attention. Visual neural responses reflect both stimulus-driven responses and attentional modulation (Carrasco, 2011; O’Craven et al., 1997; Reynolds and Chelazzi, 2004; Ungerleider, 2000). This attentional modulation is often conceptualized as a gain factor that modulates neural responses (Maunsell and Treue, 2006; McAdams and Maunsell, 1999a; Reynolds and Heeger, 2009). In numerosity processing, the balance between stimulus-driven responses and attentional modulation is unclear. Some studies use tasks (e.g., delayed match to numerosity) that draw attention to the presented numerosity (Ditz and Nieder, 2016b; Nieder and Merten, 2007; Nieder et al., 2002). Others observe similar responses without explicit numerosity tasks (e.g., color discrimination) and, speculatively, without attention to numerosity per se (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter and Dumoulin, 2021; Hofstetter et al., 2021; Tsouli et al., 2021; Viswanathan and Nieder, 2013). More recently, Castaldi et al. (2019) demonstrated that attention to a dot array’s numerosity increased numerosity’s discriminability in occipito-parietal responses, compared with attention to the same dots’ sizes. However, all these previous studies used only one dot pattern, perceived as a homogeneous single set with one numerosity. In all cases, attention was directed to the dot pattern but to different features of the dots, e.g., numerosity, size, or color.

Here, we use stimuli containing two dot patterns (subsets), letting us evaluate both attention towards and away from a dot subset. Using ultra-high field (7 T) fMRI (Cai et al., 2021b) and neural model-based analyses (Dumoulin and Wandell, 2008), we determined how numerosity-tuned responses change with attention to different subsets of items within the display.

## RESULTS

### Behavioral tasks modulate attention

Experiment 1 presented a stimulus with black-and-white-dot subsets. We fixed total numerosity (Figure 1A) and systematically varied the two subsets’ numerosities (Figures 1B and 1C). We instructed participants to attend to (the shape of) one or the other subset with a verbal instruction (“attend black” or “attend white”). Participants pressed a button when the dots of the attended subset changed from circular to oval. Ovals’ aspect ratios were adjusted to equate difficulty between participants (Table S1). No numerosity judgements were required. We presented the same stimulus, regardless of the attended subset.

We quantified task performance using the discriminability index ( $d'$ ) (Figure 1D). This was significantly higher for the attended

than unattended subset in both the attend black and attend white conditions (paired t test;  $t_{ab} = 22.6$ ,  $p_{ab} = 8.2 \times 10^{-21}$ ;  $t_{aw} = 19.3$ ,  $p_{aw} = 8.5 \times 10^{-19}$ ) (Table S1). The  $d'$  for the unattended dot subset (mean + SD:  $0.89 \pm 0.25$ ) was lower than the mean ( $1.13 \pm 0.24$ ) of a simulated  $d'$  null distribution driven by accidental hits (Figure S1). Therefore, consistent with participant reports, this  $d'$  was at chance and driven by accidental responses to the attended dot subset (i.e., false alarms), because responses within 2 s of shape changes counted as hits. This shows participants were attending and responding to the cued dot subset only.

### Numerosity responses follow the numerosity of the attended set

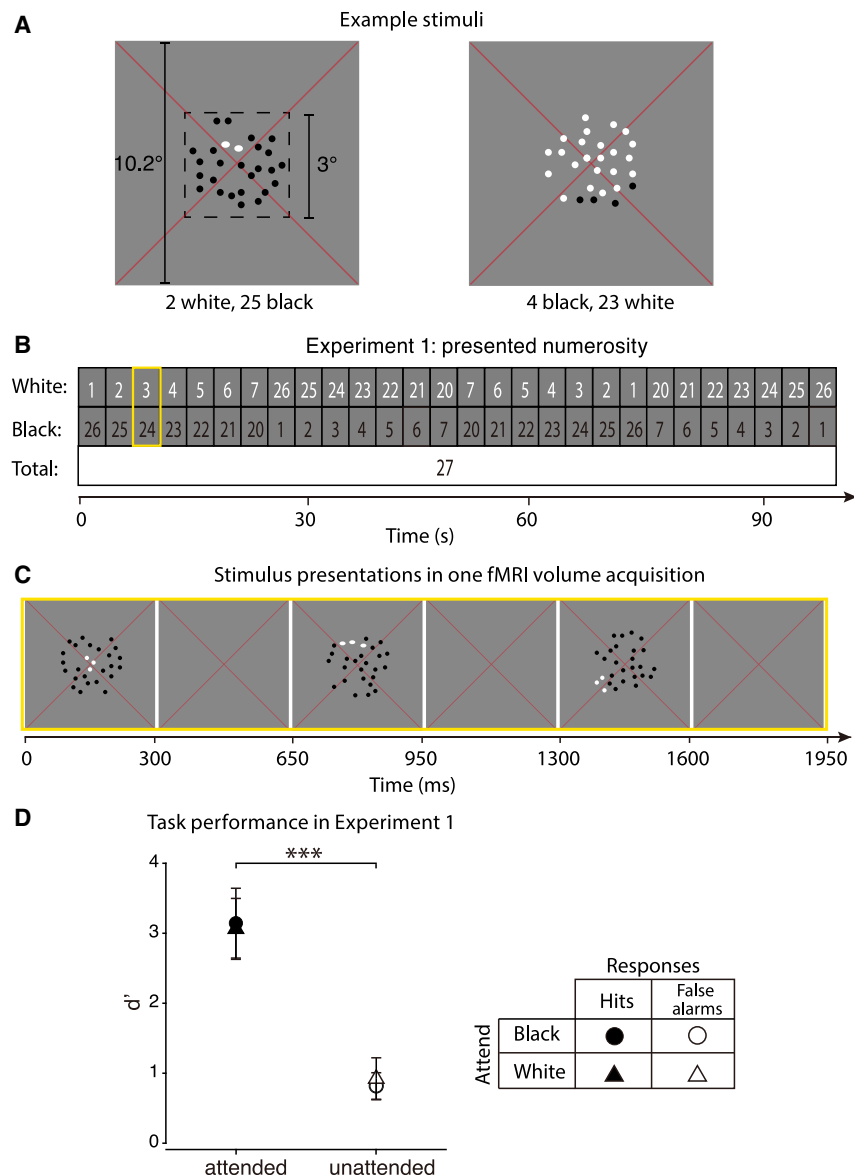
To show the attentional modulation of numerosity-tuned responses, we took fMRI time courses from the attend black and attend white condition of a single example recording site in the right superior parietal lobule of one participant (Figure 2A, black point). Although 27 dots were always displayed, these time courses (Figure 2B, left panel) show opposite neural-response patterns, with peak responses after low numerosity displays in the attended set in both conditions. This shows the underlying neural populations’ responses are modulated by which subset was attended. We fit a numerosity pRF model using only the numerosity of the attended set, which predicted most of these time courses’ response variance ( $R^2 > 70\%$ ) (Figure 2B, left panel). The pRF models give similar preferred numerosity estimates in both conditions (Figure 2B, right panel). Therefore, numerosity-tuned responses follow the attended subset’s numerosity.

We split the data into two halves and performed cross-validation using within- and between-condition validations. Model parameters determined from one data half closely predicted responses to the attended numerosity in the other half, regardless of which dot subset was attended (Figure 2C). A repeated-measures ANOVA shows no significant difference in model fits between the cross-validation combinations ( $p = 0.125$ ; Bonferroni corrected for multiple comparisons). Therefore, numerosity-tuned responses followed the attended subset’s numerosity similarly, regardless of which dot subset was attended.

As previously shown (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter et al., 2021; Tsouli et al., 2021), we found a network of topographic maps, where preferred numerosity varied gradually across the cortical surface (Figures 2D and S2). Numerosity maps derived from the two attention conditions were similar, indicating their neural populations’ preferred numerosities were independent of the attended subset. The preferred numerosity estimates from the two conditions were correlated (two-sided Wilcoxon signed rank test of correlation coefficients;  $z = 5.97$ ;  $p = 2.4 \times 10^{-9}$ ), indicating a similar spatial distribution of neural populations’ numerosity preferences on the cortical surface (Figure 2E).

### No stimulus-driven response of the preferred but unattended numerosities

Experiment 1 established that neural responses are dominated by the attended set’s numerosity but does not reveal the neural response to the unattended set. The unattended set may elicit



**Figure 1. Stimuli, study design, and task performance in experiment 1**

(A) Two example stimuli. A large, thin red fixation cross passed diagonally through the display center. A dot pattern consisting of black and white dot subsets covered the center of a gray screen. Twenty percent of stimulus presentations (10% for each subset) showed oval dots instead of circles, e.g., left panel white dots.

(B) Presented numerosity stimulus sequence.

(C) An example numerosity stimulus (yellow box in B) from one fMRI volume acquisition (repetition time [TR] = 1,950 ms).

(D) Behavioral performance (as discriminability index [ $d'$ ]) was greater for attended (hits, filled markers) than unattended subsets (false alarms, open markers). Error bars represent standard deviation over runs and participants ( $n = 32$ ). \*\*\* $p < 0.0001$  by paired  $t$  test.

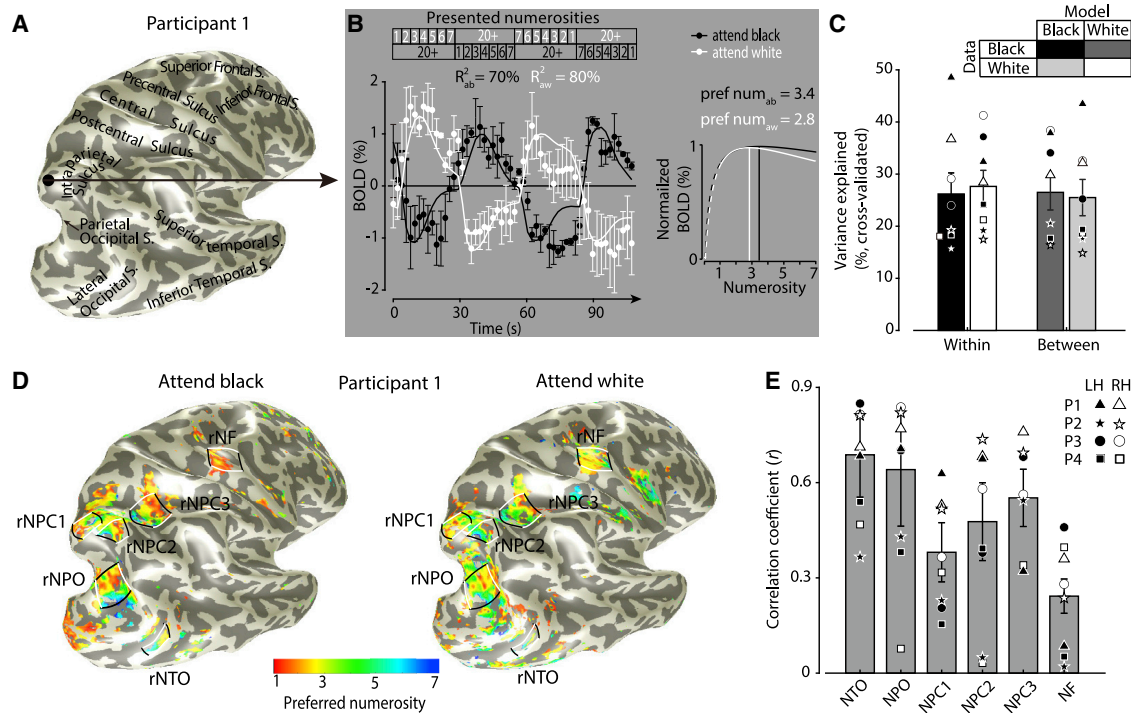
attended numerosities but less than to preferred and attended numerosities. This hypothesis follows visual cortical responses where attention boosts responses but a stimulus-driven response remains without attention (O'Craven et al., 1997). In hypothesis 2, there is no response to the preferred but unattended numerosities: neural responses follow the attended numerosity only. Note that hypothesis 2 predicts a response amplitude below zero during the block of preferred but unattended numerosities: here, the attended set's numerosity (36, 37, or 38) is further away from the preferred numerosities (two, three, or four) than the baseline numerosity (20) is.

We extracted and averaged the time courses of voxels with preferred numerosities two to four (defined from experiment 1) in all numerosity maps. We fit general linear models (GLMs) to these time courses (Figure 3D). For each map, response amplitudes of preferred numerosities in the attended set and unattended set were computed, compared with the baseline of 20 dots in both sets (Figure 3E). In line with the region of interest (ROI) definition,  $t$  tests showed significantly increased response amplitudes when the dot subset with the preferred numerosities was attended. Furthermore, in line with hypothesis 2, response amplitudes were significantly decreased when the preferred numerosities were in the unattended set. A repeated-measures ANOVA on the response amplitudes showed a significant main effect for attention ( $F_{(1, 2)} = 81.577$ ;  $p = 0.012$ ). There was no significant main effect of map ( $F_{(5, 10)} = 1.140$ ;  $p = 0.400$ ) or interaction between attention and map ( $F_{(5, 10)} = 0.877$ ;  $p = 0.530$ ). Therefore, we see no stimulus-driven response increase to preferred but unattended numerosities.

smaller responses, no response, or even suppressive responses to its numerosity. Experiment 2 used a  $2 \times 2$  block design to establish the response amplitude to preferred but unattended numerosities.

Here, we focused on neural populations preferring numerosities of two to four in the numerosity maps (see STAR Methods, "definition of regions of interest"). We presented dot subsets with preferred numerosities (two, three, or four) in the first block and third block, while being attended and unattended (Figure 3A). Total numerosity was fixed at 40, so during these blocks, the other presented numerosity was 38, 37, or 36. See task performance of experiment 2 in Figure S3.

We predicted response time courses (Figure 3B) and response amplitudes (Figure 3C) following two hypotheses (see STAR Methods, "generation of hypothesized time courses"). In hypothesis 1, neural populations still respond to preferred but un-



**Figure 2. Modulation of numerosity-selective neural responses by attention**

(A) Anatomical rendering of a participant's right cerebral cortex, showing cortical location of the example recording site (black point).  
 (B) (Left) Two very different fMRI time courses from this site's response to the "attend black" and "attend white" conditions. Points represent mean response amplitudes over repeated measurements ( $n = 3$ ). Despite identical stimulus presentations (top), responses follow the attended set's numerosity. The pRF models tuned to the attended set's numerosity predict both responses well (black and white lines).  $R^2$  denotes variance explained. (Right) Neural tuning models that best predict these time courses are shown. This recording site preferred similar numerosities (pref num), irrespective of the attention condition.  
 (C) Cross-validated variance explained evaluated within and between attention conditions. Bars show the mean; shapes show individual participants and hemispheres ( $n = 8$ ).  
 (D) Similar numerosity map networks derived from each attention condition. Maps show preferred numerosity estimates in those recording sites with  $R^2 > 30\%$ . White lines show maps borders following the lowest and highest preferred numerosities seen in each map. Black lines show the other borders of each map.  
 (E) Preferred numerosity estimates from two attention conditions were well correlated. Bars show the mean Pearson correlation coefficients; shapes show individual participants and hemispheres ( $n = 8$  and  $n = 7$  for NPC3). All error bars show standard errors of the mean.

### Suppression of preferred but unattended numerosities

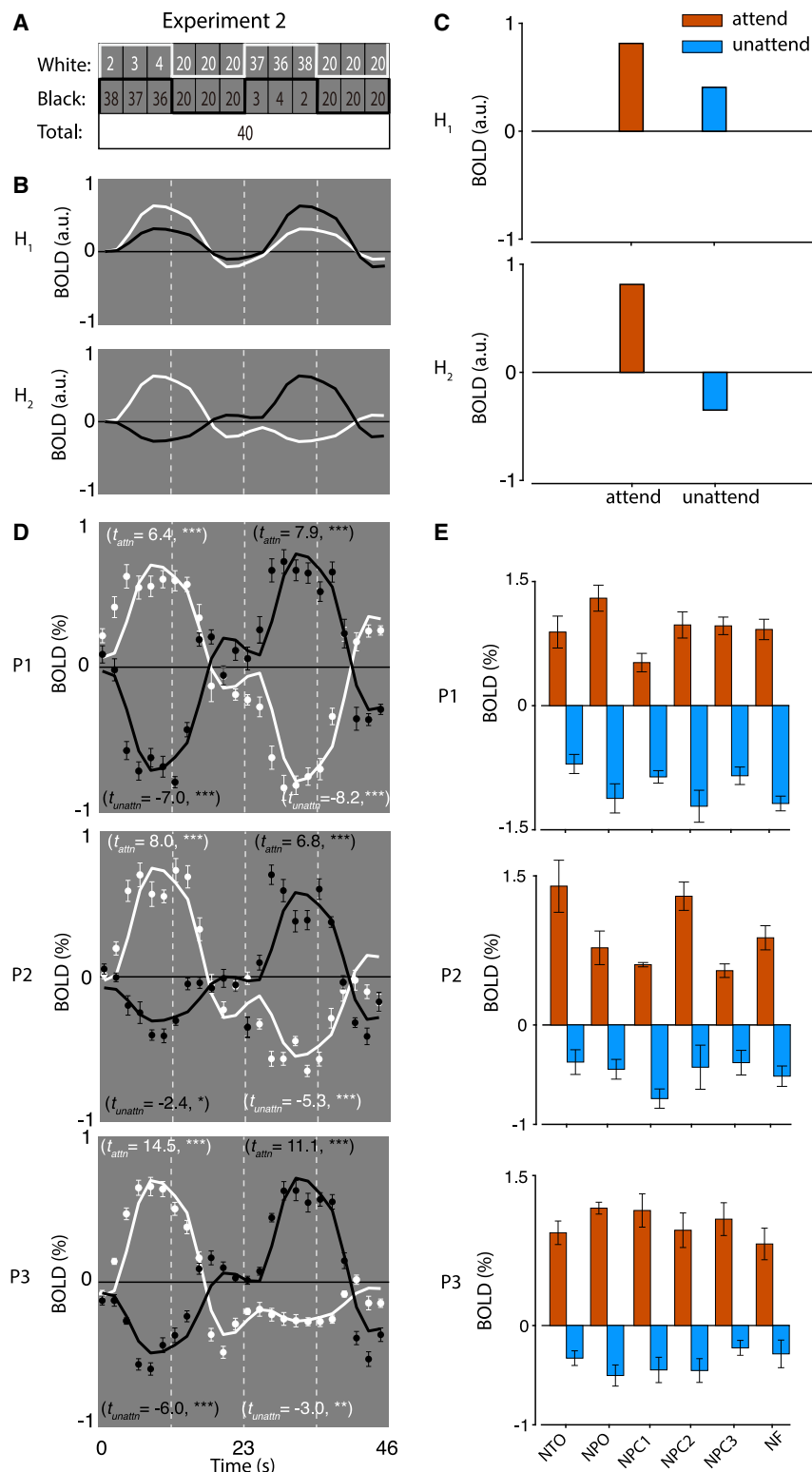
Experiment 2 kept total numerosity constant while non-preferred numerosities varied. Therefore, the source of the observed response decrease is unclear. It may be explained by the numerosity of the attended set alone: a lower response could arise because 36, 37, or 38 is further away from the preferred numerosity than 20 is. Alternatively, it could reflect suppression of the preferred numerosity's presentation in the unattended set. Therefore, experiment 3 showed only one non-preferred numerosity (20) and total numerosity varied (Figure 4A). Here, hypothesis 2 (neural responses follow the numerosity of the attended set only) predicts no decreased response when the preferred numerosities are in the unattended set (Figures 4B and 4C).

Again, neural populations' responses increased when their preferred numerosities were in the attended set. However, they still decreased (compared with baseline) when the preferred numerosities were in the unattended set, as seen in both the response time series (Figure 4D) and statistical comparisons of response amplitudes in individual maps (Figure 4E). As in experiment 2, a repeated-measures ANOVA of response amplitudes

showed a significant main effect for attention ( $F_{(1, 2)} = 19.311$ ;  $p = 0.048$ ), with no significant main effect for maps ( $F_{(5, 10)} = 1.662$ ;  $p = 0.231$ ) or interaction between attention and map ( $F_{(5, 10)} = 1.065$ ;  $p = 0.434$ ). This result goes against hypothesis 2's prediction that neural responses follow the attended set's numerosity only and are unaffected by the unattended set. The below baseline responses to preferred numerosities in the unattended set suggest that, without attention, preferred numerosities actively suppress neural population responses.

### DISCUSSION

Our results suggest that attention drives numerosity responses. In animals, numerosity-tuned responses are typically measured during thoroughly trained numerosity comparison tasks (Ditz and Nieder, 2015; Nieder and Merten, 2007; Nieder et al., 2002) that require attention to both the dot set and its numerosity. Similar responses are found in untrained animals that attended the dot set's color but attended the dot set nevertheless (Viswanathan and Nieder, 2013). Likewise, our previous studies used a dot-color



**Figure 3. Study design, hypotheses, and responses in experiment 2**

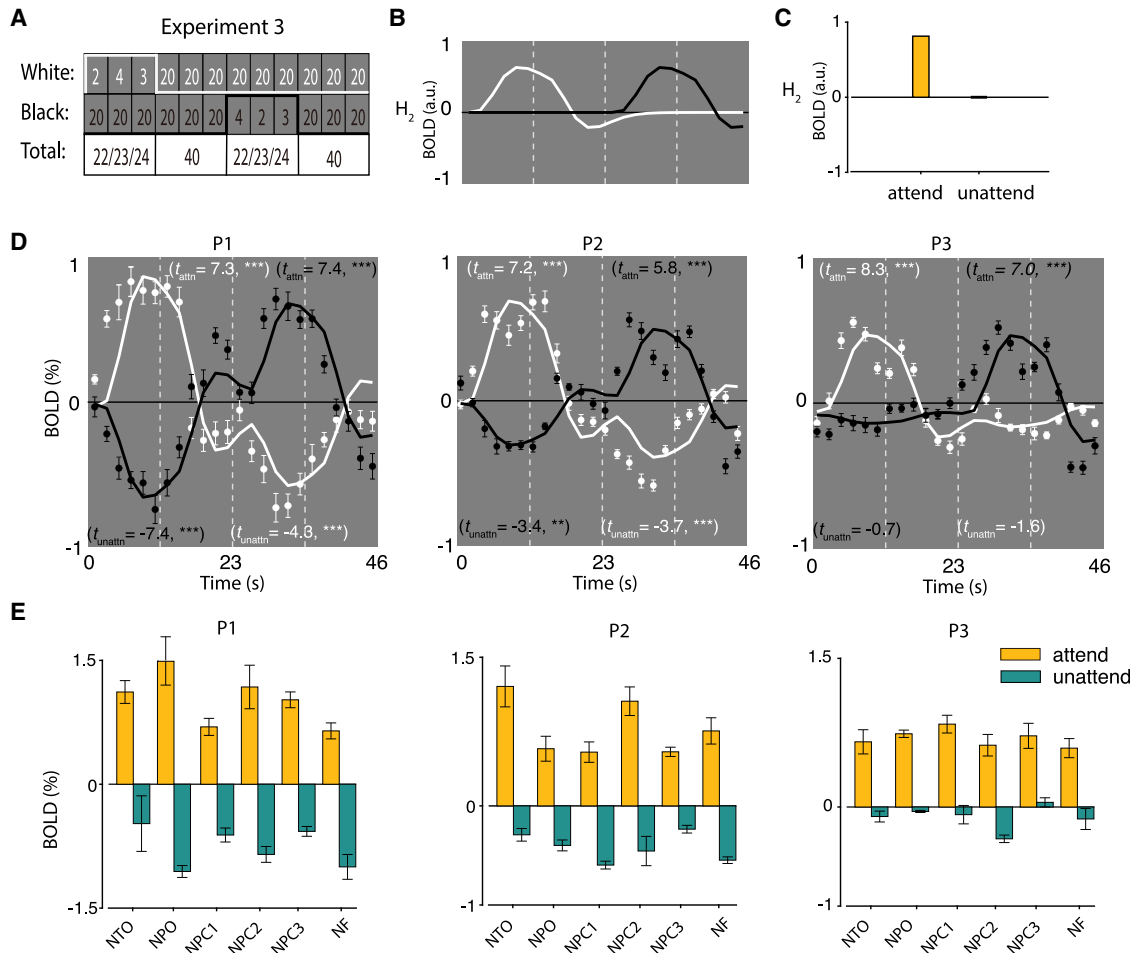
(A) Experimental design. Stimuli consisting of a subset of two, three, or four dots (the preferred numerosity) in one color and another subset of 38, 37, or 36 dots in the other color, or two equal subsets of 20 dots, are presented simultaneously.

(B) Hypothesized numerosity responses under attentional modulation in the two conditions. Hypothesis 1 (H<sub>1</sub>) is that neural responses follow preferred numerosities, with stronger responses when these are in the attended set but some small responses when they are in the unattended set. Hypothesis 2 (H<sub>2</sub>) is that neural responses follow the attended numerosity only, with responses to preferred numerosities in the attended set and no response or decreased responses when they are in the unattended set. Black and white lines indicate the attend black and attend white conditions, respectively.

(C) Predicted response amplitudes to preferred numerosities in the attended set (red) and unattended set (blue) following H<sub>1</sub> (top) and H<sub>2</sub> (lower).

(D) Measured response time courses and general linear model (GLM) predictions. Compared with the baseline of 20 dots in both subsets, increased responses occurred when preferred numerosities were in the attended set, while decreased responses occurred when they were in the unattended set. Points represent mean response amplitudes over repeated measurements ( $n = 7$ ). Solid lines show GLM predictions.  $T$  values demonstrate statistically significant difference in response amplitudes in conditions where preferred numerosities were in the attended ( $t_{\text{attn}}$ ) or unattended set ( $t_{\text{unattn}}$ ), compared with the baseline, in each condition. \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.0001$ .

(E) Averaged response amplitudes when the preferred numerosities were in the attended (red) and unattended (blue) sets across two conditions in individual maps. All error bars show standard errors of the mean.



**Figure 4. Suppressive neural population responses to preferred but unattended numerosity**

(A) Study design of experiment 3. A subset of two, three, or four dots was either attended or unattended while keeping the non-preferred numerosity constant at 20.

(B) Predicted responses following hypothesis 2: neural responses follow the numerosity in the attended set only, with no response to the preferred numerosity in the unattended set.

(C) Predicted response amplitudes when the preferred numerosities are in the attended set (yellow) and unattended (green) set.

(D) Measured response time courses (points: mean response amplitudes over repeated measurements [ $n = 7$ ]) and GLM predictions (lines). Compared with the baseline of 20 dots in both subsets, increased responses occurred when preferred numerosities were in the attended set, while decreased responses occurred when they were in the unattended set. Black and white symbols indicate the attend black and attend white conditions, respectively.  $T$  values show significant differences in response amplitudes in conditions where preferred numerosities were in the attended ( $t_{\text{attn}}$ ) or unattended set ( $t_{\text{unattn}}$ ), compared with the baseline, in each condition. \*\* $p < 0.01$ ; \*\*\* $p < 0.0001$ .

(E) Averaged response amplitudes when the preferred numerosities were in the attended set (yellow) and unattended set (green) across two conditions in individual maps. All error bars represent standard error of the mean.

task to ensure participants attended the dot set (with no numerosity judgements required) (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter and Dumoulin, 2021; Hofstetter et al., 2021; Tsouli et al., 2021). Castaldi et al. (2019) demonstrate that attention modulates numerosity-specific activation in the human parietal cortex by comparing numerosity or size judgments. In that case, the whole stimulus was attended but different features. By contrast, in our case, one subset of the dot pattern was attended in a shape task and no numerosity judgements were required. Thus, the attended feature, i.e., dot shape, remains constant throughout our experiments.

In visual cortex, attention enhances stimulus-driven responses of neurons preferring the attended location or feature (Corbetta et al., 1990; Treue and Maunsell, 1996). For example, attention increases responses of neurons tuned to location (Connor et al., 1997; Moran and Desimone, 1985), orientation (McAdams and Maunsell, 1999a; 1999b), and motion direction (Treue and Martínez Trujillo, 1999). Even the attended feature within a complex display affects response amplitudes: with both stationary and moving dots shown, attention to the moving dots produces larger response than attention to the stationary dots in area middle temporal (MT) (O'Craven et al., 1997). Yet, even



with attention diverted away, motion still elicits some (stimulus-driven) neural response. This appears different from our results, where attention seems required for numerosity-tuned neural responses, driving or gating the responses.

Castaldi et al. (2019) find significant numerosity-decoding accuracy, even when participants judged size, but not numerosity. This suggests attention to the stimulus (not necessary to its numerosity) can elicit numerosity responses. Indeed, previous studies of ourselves and others always required attention to the numerosity stimulus, not purely passive viewing (Cai et al., 2021a; Eger et al., 2009; Harvey et al., 2013a; Hofstetter et al., 2021; Piazza et al., 2004). However, several studies demonstrate that numerosity is perceived spontaneously when a stimulus is viewed (Anobile et al., 2016b; Burr and Ross, 2008; Cicchini et al., 2016; Nieder and Dehaene, 2009), so some attention to numerosity may occur unless attention is strongly focused elsewhere (as in our experiments). Thus, unlike early visual responses, which happen whenever the preferred stimulus is shown (i.e., stimulus driven), we propose that both bottom-up and top-down mechanisms appear necessary to numerosity-tuned neural responses. We speculate that this may be because numerosity-tuned responses emerge later in visual processing (Paul et al., 2022), while orientation-tuned (McAdams and Maunsell, 1999a; 1999b), motion-direction-tuned (Treue and Martínez Trujillo, 1999; Treue and Maunsell, 1996), and spatially tuned (Connor et al., 1997; Martínez-Trujillo and Treue, 2004) responses are present in early visual cortex.

We found suppressive responses in numerosity-tuned neural populations when their preferred numerosity was in the unattended set. Simultaneously, the attended set has numerosities further from the preferred numerosity. These suppressive responses appeared as “negative” blood-oxygen-level-dependent (BOLD) responses. However, fMRI signals have no units, so response amplitudes were normalized (see STAR Methods) and negative responses are always relative to a baseline. It is very difficult to infer inhibitory neural responses from fMRI, as the BOLD signal reflects the local input and intracortical processing (Logothetis, 2002). However, negative responses have been correlated with decreases in neural activity (Shmuel et al., 2006). Moreover, attention can be viewed as a neural resource allocated to a stimulus, which may affect mutual inhibition between nodes in a priority map framework (Knops et al., 2014). Therefore, we speculate that these suppressive responses reflect a suppression or inhibition of the underlying numerosity-tuned neurons.

Recent findings show that response facilitation when the attended feature matches the neuron’s response preference is accompanied by response suppression in neurons with preferences far from the attended feature. Specifically, Martínez-Trujillo and Treue (2004) recorded direction-tuned responses in macaque area MT while systematically changing the direction attended outside the neurons’ receptive fields. Changing from a neuron’s preferred to its anti-preferred direction change the attentional modulation from an enhancement to a suppression. This finding is considered evidence that attention modulates a neuron’s overall responsiveness based on the difference between its preferred stimulus feature and the currently attended stimulus features: the feature similarity gain model (Maunsell

and Treue, 2006; Treue and Martínez Trujillo, 1999; but see Stalder et al., 2021). In this context, our observed suppressive responses could be attributed to little similarity between the preferred numerosity (e.g., two, three, or four) and the attended set’s numerosity (e.g., 36, 37, or 38). However, experiment 3 showed similar negative responses (not a baseline response) to the baseline numerosity of 20 in the attended set, suggesting the preferred but unattended dot subset induced these suppressive responses.

Our results may be explained by a normalization model of attention with three basic components: a stimulation field, a normalization field, and an attention field (Reynolds and Heeger, 2009). Previous visual-processing studies show that directing attention to a distracter outside the receptive field can reduce the response elicited by a preferred stimulus in the receptive field of a relevant neuron (Moore and Armstrong, 2003; Motter, 1993), consistent with divisive surround suppression. Surround suppression of visual spatial responses elicits negative fMRI responses in early visual cortex (Aqil et al., 2021; Harvey et al., 2013b; Zuiderbaan et al., 2012). In addition, the attention field acts as a gain field and that may have a suppressive surround (Puckett and Deyoe, 2015). These findings suggest attention has both facilitatory and suppressive components that may both affect numerosity-selective neural responses.

Experiment 1 shows that neural responses are dominated by the attended set’s numerosity. However, these responses might combine responses to both attended and unattended sets. Theoretically, the observed modulated responses might be attributed to (1) enhanced responses to preferred numerosity in the attended set, (2) suppressive responses to non-preferred numerosity in the unattended set, or (3) a combination of these enhanced and suppressive responses. Given the large literature that attention boosts responses (Carrasco, 2011; Hillyard et al., 1998; Hopfinger et al., 2000; O’Craven et al., 1997), we assume the observed neural responses are driven by attention to the attended set alone. But given the suppressive responses in follow-up experiments, a combination is feasible.

Can our results be explained by other features of our stimulus or task, such as perceptual grouping by spatial proximity or shape (Anobile et al., 2020; Maldonado Moscoso et al., 2020; Zhao and Yu, 2016)? The spatial distribution of the two dot subsets is unlikely to account for the observed effect of attention. First, the subsets with the preferred and non-preferred numerosity were displayed simultaneously. Second, the position the dot subsets were randomized on each display so no location was associated with any particular numerosity. Finally, the shape of the dots was changed homogeneously within the same dot subset; thus, there was no grouping effect within each dot subset.

To summarize, attention to a group of items strongly modulates neural responses to its numerosity, even when numerosity itself is not task relevant or endogenously attended. We propose that both lower level and higher level processes are required in numerosity responses. On one hand, numerosity-tuned responses occur even without explicit numerical tasks, including the current study (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter et al., 2021; Tsouli et al., 2021; Viswanathan and Nieder, 2013). On the other hand, higher level cognitive processes, like attention, also play

important roles in processing numerical information. We live in a complex world in which a single scene may have many different types of objects with different numerosities. Representing the numerosity of task-relevant objects while ignoring the numerosity of other objects may therefore be vital to the effective numerosity perception in natural scenes.

### Limitations of the study

First, we scanned four participants for at least two to four sessions in three experiments (roughly 6 h per participant total). This sample size is relatively small and focuses on high number of trials per participant, maximizing signal and minimizing noise (Gratton et al., 2022). Moreover, statistical power is determined both by the number of participants and the number of trials per participant (Baker et al., 2020): studies with fewer participants but more trials can have the same statistical power as more participants with fewer trials (Cai et al., 2021b). Furthermore, all the participants exhibited similar results, i.e., participants are replication units not measurement units. Second, the center-surround effect of attention field was not tested here, in respect to numerosity, but could be addressed in future projects. Third, our findings suggested that attention is a necessary ingredient in numerosity processing, and we proposed that both bottom-up and top-down mechanisms are involved in numerosity processing. However, the underlying neural substrates of these mechanisms were not fully investigated. Last, we measured neural responses with fMRI, which reflects the pooled responses of a large population of neurons at each measurement site (voxel). These results are therefore indicative of the majority of neuronal responses, but not the variability of neuronal responses, i.e., it is possible that a minority of neurons respond independently of the effects of attention.

### STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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### SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.celrep.2022.111005>.

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### AUTHOR CONTRIBUTIONS

Conceptualization, Y.C., S.H., and S.O.D.; study design, Y.C., B.M.H., and S.O.D.; data collection and analysis, Y.C.; writing – original draft, Y.C.; writing – review & editing, Y.C., S.H., S.O.D., and B.M.H.; supervision, S.H. and S.O.D.; funding acquisition, S.O.D. All authors approved the final version of the manuscript for submission.

### DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

### KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Vistasoft repository	<a href="https://github.com/vistalab/vistasoft/">https://github.com/vistalab/vistasoft/</a>	<a href="https://github.com/vistalab/vistasoft/">https://github.com/vistalab/vistasoft/</a>
MATLAB R2019b	MathWorks	<a href="https://www.mathworks.com">https://www.mathworks.com</a>
AFNI (version 17.0.13)	National Institute of Mental Health	<a href="https://afni.nimh.nih.gov/">https://afni.nimh.nih.gov/</a>
CBS tools (version 7.4.0)	Max Planck Institute	<a href="https://www.cbs.mpg.de/institute/software/cbs-tools">https://www.cbs.mpg.de/institute/software/cbs-tools</a>
ITK-SNAP (version 1.6.0.1)	<a href="http://www.itksnap.org/pmwiki/pmwiki.php">http://www.itksnap.org/pmwiki/pmwiki.php</a>	<a href="http://www.itksnap.org/pmwiki/pmwiki.php">http://www.itksnap.org/pmwiki/pmwiki.php</a>
JASP (version 012.2.0)	<a href="https://jasp-stats.org/">https://jasp-stats.org/</a>	<a href="https://jasp-stats.org/">https://jasp-stats.org/</a>

### RESOURCE AVAILABILITY

#### Lead contact

Further information and requests for resources, data, and code should be directed to and will be fulfilled by the lead contact, Serge O. Dumoulin ([s.dumoulin@spinozacentre.nl](mailto:s.dumoulin@spinozacentre.nl)).

#### Materials availability

This study did not generate new unique reagents.

#### Data and code availability

- The datasets supporting the current study have not yet been deposited in a public repository because of participants privacy concerns, but are available from the [lead contact](#) on request.
- The code that supports the findings of this study is publicly available in the Vistasoft repository. DOIs are listed in the [key resources table](#).
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

### EXPERIMENTAL MODEL AND SUBJECT DETAILS

We present data from four participants in three different consecutive experiments (two females, age range 27–32 years). All the participants had normal or corrected-to-normal visual acuity. All were well educated, with good mathematical abilities. Written informed consent was obtained before every MRI session. All experimental procedures were approved by the ethics committee of VU University Amsterdam.

### METHOD DETAILS

#### Stimuli and experimental design

Visual stimuli were presented on a 69.84 × 39.29 cm LCD screen (Cambridge Research Systems) behind the MRI bore. Participants were required to lie still and view the display through a mirror attached to the head coil. The total distance from the attached mirror to the display screen was 220 cm. The display resolution was 1920 × 1080 pixels. A button box recorded behavioral responses. Visual stimuli were generated in Matlab using PsychToolbox (Kleiner et al., 2007). In all the experiments, a large diagonal cross composed of thin red lines was displayed consistently across the entire screen, serving as a fixation marker. The numerosity stimuli consisted of black and white dots presented simultaneously in the central 3° (diameter) of the visual field. In 10% of the total stimuli presentations, black dots were shown in ovals instead of circles, and in another 10% of the stimulus presentations, white dots were shown as ovals. The aspect ratio of the ovals was adjusted in practice runs prior to scanning so that difficulty was equated between participants (for aspect ratios for each participant see [Table S1](#)). At the start of each scan run, participants were verbally instructed which group they should pay attention to through the scanner's intercom system, using the instructions 'attend black' or 'attend white'. The order of these two conditions alternated every two runs in each session, and was counterbalanced between sessions in the same participant. Participants fixated the red cross throughout the experiments, and pressed a button when they detected a subtle shape change (from circular to oval) of the group they were instructed to pay attention to. No numerosity judgement was required. Task performance was

quantified using the discriminability index ( $d'$ ) of the signal detection theory, which denotes participants' sensitivity to the difference between the signal present and signal absent distributions (Green and Swets, 1966). We determined a response as a hit if it occurred within 2 s after a signal presentation, otherwise it was classified as a false alarm.

### Experiment 1

In previous studies, the stimulus systematically varied total numerosity (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter and Dumoulin, 2021; Hofstetter et al., 2021; Tsouli et al., 2021). In Experiment 1, we fixed the total numerosity (i.e. 27 dots) and systematically varied the ratio of black and white dots. Specifically, the numerosity stimulus consisting a subset of black dots and another subset of white dots in the same display. The numerosities of these two sets systematically increased and decreased to map responses to their numerosities, but the changes of the two subsets were coordinated so the total numerosity of the whole display remained constant at 27. The dots were randomly positioned at each presentation so that each dot fell entirely within the stimulus area and no specific visual position was associated with any numerosity. Individual dots were distributed roughly homogeneously to avoid perceptual grouping. Dots in the subset with a smaller set size were presented next to each other (Figure 1A).

We used a similar design as was previously used to uncover numerosity maps (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Harvey et al., 2013a; Hofstetter and Dumoulin, 2021; Hofstetter et al., 2021; Tsouli et al., 2021). Specifically, the numerosity of the white dot subset increased from 1 to 7, while the black dot subset decreased from 26 to 20 (Figure 1B). Then, the black dot subset increased from 1 to 7, while the white dot subset decreased from 26 to 20. Then, the white dot subset decreased from 7 to 1, while the black dot subset increased from 20 to 26. Finally, the black dot subset decreased from 7 to 1, while the white dot subset increased from 20 to 26. This sequence was repeated three times at each functional run. Participants 1 and 3 were shown with this presentation sequence, while the other participants were shown with the same sequence but in the opposite dots color (i.e. first the black dot subset increased from 1 to 7, while the white dot subset decreased from 26 to 20 accordingly). We analysed the responses to the stimuli focusing the numerosity of the attended set. For example, when participants attended the white dot subset ('attend white' condition), the numerosity of the attended set first increased from 1 to 7, then decreased from 26 to 20, then decreased from 7 to 1, then increased from 20 to 26. We have previously shown that most numerosity-tuned neural populations have a numerosity preference below seven (Cai et al., 2021a). When the numerosity of the attended set was in the 1–7 range, we therefore expected a large response from these neural populations and a large modulation of the response by the changes in numerosity. When the numerosity of the attended set was in the 20–26 range, we expected little response from these neural populations and little modulation of the response as well. Thus, a long period of attending a dot subset with a large numerosity serves as a baseline period, allowing the haemodynamic responses to return to baseline.

Each numerosity dot pattern was presented briefly (300 ms) to ensure participants did not have time to count (Figure 1C). A new random pattern was presented every 650 ms, with a 350 ms presentation of a uniform grey background between dot pattern presentations. This was repeated three times, over 1950 ms, corresponding to one fMRI volume acquisition (i.e., TR). Each numerosity was presented six times, corresponding to 2 TRs, before moving to next numerosity in the stimulus sequence.

### Experiment 2

In order to investigate the extent to which numerosity responses were modulated by numerosity preference and attentional state, we applied a 2 (preferred numerosity vs. non-preferred numerosity)  $\times$  2 (attended vs. unattended) block-design experiment (Figure 3A). We focused on the neural populations that had preferred numerosities of 2–4, determined from Experiment 1, given that the large proportions of neural populations tuned to these numerosities (Cai et al., 2021a; Nieder and Merten, 2007). To maintain a constant total numerosity of 40 in the stimulus displays, the stimuli consisted of a small subset of 2/3/4 dots and a large subset of 38/37/36 dots in the opposite color, or two equal-sized subsets of 20 black dots and 20 white dots.

Each dot pattern was presented similarly to Experiment 1 with 300 ms presentation of a dot pattern followed by 350 ms presentation of a grey background. This was repeated six times for each numerosity when the stimuli consisted of variable-sized dot subsets (presentations of 2+38, 3+37 or 4+36 dots) and 18 times when the stimuli consisted of two equal-sized subsets (presentations of 20+20 dots). The presentations of the numerosities of 2/3/4 were randomized within the block, yet keeping the total numerosity to 40 dots. The total surface area of each dot pattern remained constant.

The stimuli were presented in four blocks, each block lasted 11.7 s. As in Experiment 1, participants were informed to which dot subset they should perform a shape change detection task on by verbal instructions at the start of each scan run. This block-design stimulus sequence was repeated seven times at each run. This block structure produces robust BOLD responses, ensuring a sufficient blank period for the hemodynamic responses to return to baseline between blocks.

### Experiment 3

In Experiment 2 the non-preferred numerosities varied to match the preferred numerosity so as to remain the total numerosity constant at 40. Thereby the non-preferred numerosities in the attended or unattended set also varied. To further understand numerosity responses to preferred numerosities in the unattended set, in Experiment 3 we fixed the non-preferred numerosity at 20, both in the attended or unattended set. Specifically, we used stimuli that consisted of a subset of 2/3/4 dots in one color and another subset of 20

dots in the opposite color, or two equal subsets of 20 black dots and 20 white dots (Figure 4A). In other words, the non-preferred numerosity was constant but the total numerosity varied. Stimulus presentations were identical to Experiment 2.

### MRI acquisition and preprocessing

MRI data were acquired from a Philips 7 Tesla scanner (Philips Medical Systems, Best, Netherlands). T1 anatomical data were acquired with an MP2RAGE sequence (Marques et al., 2010) at the spatial resolution of  $0.7 \text{ mm}^3$ , repetition time (TR) was 6.2 ms, echo time (TE) was 2.5 ms, and flip angle (FA) was 5 degrees. Functional T2\*-weighted two-dimensional echo planar images (EPI) were acquired using a 32-channel head coil (Philips Nova Medical) with the following parameters: isotropic resolution of  $1.75 \text{ mm}^3$ , full-brain-coverage field of view (FOV =  $234 \times 112 \times 184 \text{ mm}$ ) covering 64 slices, TR/TE = 1950/25 ms, and FA =  $70^\circ$ , multi-band factor = 2. Each functional run had 174 TRs and lasted 339.3 s. Top-up scans that included the opposite phase-encoding direction were acquired following each functional run. Each scanning session included eight functional runs. Experiment 1 included two scanning sessions that were collected on separate days, resulting in eight runs for the 'attend black' and 'attend white' conditions, respectively. Three of the participants were scanned for Experiments 2 and 3 on separate days. Each experiment had one session including eight runs. The order of the two attention conditions was randomised between sessions and participants. One functional run of the 'attend black' condition in Experiment 1 of Participant 3 was excluded due to signal dropout in the image data.

T1 anatomical scans were resampled to an isotropic resolution of  $0.6 \text{ mm}^3$  and preprocessed and automatically segmented grey and white matter using cbs-tools (<https://www.cbs.mpg.de/institute/software/cbs-tools>). Segmentation errors were manually edited using ITK-SNAP (Yushkevich et al., 2006). The cortical surface was reconstructed at the grey-white matter border and rendered as a smoothed 3D surface. Functional runs were corrected for head movement and motion using AFNI (Cox, 1996). Image distortions in the gradient encoding direction were corrected for using the top-up scans (Andersson et al., 2003). The first six TRs of each functional run were discarded to ensure steady-state magnetization. Functional runs were registered to the anatomical images using *vistasoft* (<https://github.com/vistalab/vistasoft>). Functional data were interpolated to the anatomical segmentation space using trilinear interpolation. Functional runs from separate sessions were imported to the same T1-weighted anatomical space. The time-series data were then aligned to the anatomical space and then averaged based on the attention conditions in each experiment, respectively. Data from all recording sites (voxels) were collapsed and averaged onto the nearest point on the cortical surface, which generated a (folded) two-dimensional representation of the grey matter nodes and increased signal strength. The fMRI data were analysed at this space with pRF modelling (Experiment 1) and GLM analyses (Experiments 2 and 3). No spatial or temporal smoothing was applied to the functional data.

### pRF modelling

pRF modelling was applied to the fMRI data collected in Experiment 1 in order to characterize the numerosity tuning of each recording site in the attention conditions (Dumoulin and Wandell, 2008). Briefly, to characterize numerosity tuning, the pRF model describes the averaged tuning of the underlying neural populations using a one-dimensional logarithmic Gaussian function (Harvey et al., 2013a). The Gaussian function is characterized by preferred numerosity (mean of the Gaussian) and tuning width (standard deviation of the Gaussian).

The pRF model is estimated based on the fMRI data and the time course of the presented numerosities. In Experiment 1 the total presented numerosity was constant (i.e. 27 dots) throughout the time course and so predicts a constant response and explains no response variance. However, the numerosity of the attended set changed, so the pRF model was fitted to the attended set's numerosity rather than the total numerosity. For a large group of candidate preferred numerosities and tuning widths, a predicted neural response time course is calculated by taking the attended set's numerosity at each time point and evaluating the candidate Gaussian function's amplitude at each numerosity in the stimulus time course. Each candidate predicted neural response time course is then convolved with a canonical hemodynamic response function (HRF) to create a candidate predicted fMRI time course. The predicted fMRI time course that brings the best agreement to the measured fMRI time course at this recording site was chosen. Participant-specific HRF parameters were estimated over the whole fMRI volume and applied to refit the pRF (Harvey and Dumoulin, 2011). The Gaussian function's parameters that generated the best fit fMRI time course were used to characterize the response at this recording site. The pRF fitting procedure allows preferred numerosity estimates outside the range of the numerosities in the attended set, ensuring estimates within the stimulus range are not just the best of a limited set.

### Definition of regions of interest

We rendered the preferred numerosities of the response model from the average of both attention conditions in Experiment 1 onto the cortical surface. We excluded recording sites where the preferred numerosity was outside the main attended numerosity range (i.e. 1–7) or the variance explained by the pRF model was lower than 30% from further analysis. Six ROIs were drawn on each hemisphere corresponding to the six numerosity maps described in previous studies (Cai et al., 2021a; Harvey and Dumoulin, 2017a; Hofstetter et al., 2021; Tsouli et al., 2021): NTO at the temporo-occipital cortex, NPO at the parietal-occipital cortex, NPC1-3 around the post-central sulcus of the parietal cortex, and NF in superior frontal cortex. In each map, we manually defined lines on the lowest and highest points of preferred numerosity ("end" borders). The edges of the map ("side" borders) were defined around local regions showing good fits of numerosity-tuned response models.



We extracted voxels within these numerosity maps that had the preferred numerosities of 2–4 and had more than 30% variance explained by the pRF models in both conditions from Experiment 1, resulting in a new ROI. This ROI was then used for further analysis in Experiments 2 and 3.

### GLM analysis

We performed GLM analyses on the fMRI data recorded in Experiments 2 and 3. The timing of presentations of the preferred numerosities in the attended set and in the unattended set served as a predictor in the GLM. This was convolved with a two-gamma HRF to account for the delayed and dispersed blood flow responses (Glover, 1999). Paired t-test was performed to demonstrate the different responses between conditions where preferred numerosities were in the attended set or in the unattended set, compared to the baseline condition, in a given condition. Response amplitudes (betas, denoted as percentage BOLD signal change) of individual maps were computed across hemispheres for individual participants. Repeated measures ANOVA analysis was performed on the response amplitudes of all participants, with the factors of attentional states and individual maps. Post-hoc analysis was performed afterwards with Bonferroni correction for multiple comparisons.

### Generation of hypothesized time courses

Following a neural tuning function with preferred numerosity of 3, we normalized the response amplitudes relative to the baseline numerosity (20) to zero, and normalized the maximum response amplitude to the preferred numerosity (3) to one. The normalized response amplitudes to preferred numerosity (2/3/4), baseline numerosity (20) and non-preferred numerosity (36/37/38) were extracted from the neural tuning function. We then multiplied these response amplitudes with the design matrix of the GLM where the presence of preferred numerosities served as a predictor. This was then convolved with a canonical two-gamma HRF to generate hypothesized time courses. In Hypothesis 1, a stimulus-driven response remains without attention, thus the response amplitude to preferred but unattended numerosity was set to be half of the maximum response (i.e. 0.5). In Hypothesis 2, the response amplitude to numerosities higher than the baseline numerosity was below zero, i.e. negative responses.

### Correlations of pRF estimates derived from two attention conditions

Pearson correlation analysis was performed between numerosity preferences estimated from the ‘attend black’ and ‘attend white’ conditions in Experiment 1. Taking into account the functional resolution of the recording sites, the total number of data points ( $n$ ) used was reduced by the factor that functional voxels were up-sampled onto the 2D cortical surface to calculate the correlation’s probability. Before the statistical test on the correlation coefficients between numerosity preferences derived from the two conditions, the correlation coefficients were transformed into z-scores using Fisher z-transformation. We showed the averaged correlation coefficients across participants and hemispheres for individual maps. Then, we performed a two-side Wilcoxon sign-rank test showing that the correlation coefficients were significantly higher than zero.

### Cross validation

We cross validated the numerosity tuning response model fits between the ‘attend black’ and ‘attend white’ conditions. Specifically, we split the data of each condition into two halves based on odd or even runs and cross-validated the pRF estimates within- and between-condition. Specifically, we fitted the numerosity pRF model on one half dataset and used this to predict the responses from the other half. We fitted that model to another dataset of the same condition or the opposite condition, giving the cross-validated variance explained ( $cvR^2$ ) in each case. We averaged the  $cvR^2$  from all the iterations of the cross validation combinations. A repeated measures two-way ANOVA analysis was performed in JASP (JASP Team, 2020) to compare the  $cvR^2$  of the within- and cross-condition validations.

## QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses described in this paper were performed using the R2019b release of MATLAB software (The MathWorks) unless indicated otherwise. Analyses were performed using paired  $t$  test to compare two conditions and repeated measures ANOVA, with post-hoc analyses with Bonferroni corrected for multiple comparisons. For cross validation analyses, a within-subject two-way ANOVA was performed in JASP. Results represent the mean  $\pm$  SEM as stated in the figure legends, unless indicated otherwise. Statistical significance is represented by \*,  $p < 0.05$ ; \*\*,  $p < 0.01$ ; \*\*\*,  $p < 0.0001$ . Sample size and statistical tests are also reported in the figure notes.