Attention alters numerosity tuning in the human brain

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Abstract

Many animals, including humans, can rapidly and accurately perceive numerosity, the number of objects. Although typically considered a cognitive function, recent studies proposed that numerosity perception instead relies on sensory processes. The brain contains numerosity-tuned neural populations that respond most strongly when passively viewing a preferred numerosity (e.g., six). Real-world vision, however, is target-oriented, and attention may alter numerosity processing. Just like spatial attention attracts neural responses to attended locations, we asked whether attention could alter numerosity preferences toward task-relevant (i.e., attended) numerosities. Using 7T fMRI and population receptive field (pRF) modeling, participants reported the occurrence of displays containing either numerosity two (low), numerosity six (high), or white stimuli (non-numerical). Neural preferences altered accordingly: lowest when attending to two, highest to six, and intermediate for color. These results show that numerosity tuning of neural populations not only depends on stimulus properties but also on the behavioral goals of the observer.

Keywords: numerical cognition; numerosity; attention; population Receptive Field (pRF); ultra-high field 7T fMRI

Introduction

Numerical cognition is an intuitive ability in humans and many animals to quickly and accurately process numerosity: the number of objects in a group (Nieder, 2025). This ability is closely linked to cognitive processes such as attention (Burr et al., 2010; Piazza et al., 2018) and working memory (Piazza et al., 2011), as well as higher mental functions, including calculation (Butterworth et al., 2011; Castaldi et al., 2020) and decision-making (Peters et al., 2006). Another line of research, however, suggests that numerosity may be processed as a low-level sensory feature (Park et al., 2015; Paul et al., 2022).

Viewing groups of objects evokes numerosity-tuned neural responses in certain neural populations. In these numerosity-tuned populations, responses peak at a specific (preferred) numerosity, and show a weaker response at increasing numerical distance (Nieder et al., 2002; Nieder & Miller, 2003).

Although typically studied under passive viewing conditions, real-world numerosity perception is likely goal-oriented: observers select or compare specific numerosities to complete everyday tasks (Johnston & Dark, 1986; Treisman, 1969). Accordingly, goal-directed attention may modulate neural responses to numerosity (Cai et al., 2022). But it remains unknown whether and how goal-directed attention to a specific numerosity affects the numerosity tuning of neural populations. To address this, we combined ultra-high field (7T) fMRI and

the population receptive field to test how attention to specific numerosities alters the preferred numerosity of numerosity-tuned neural populations in the human brain (Dumoulin & Wandell, 2008; Harvey et al., 2013).

Method

We recruited seven human participants (one female; age range 23-48 years). Stimuli consisted of dot arrays with six numerosities (1, 2, 3, 4, 6, 12), presented in either black or white. In each scanning run, participants were instructed to attend to one of three targets: numerosity 2 (low), numerosity 6 (high), or white-colored dots (non-numerical baseline). Each scanning run contained sequences with targets and without targets, allowing us to measure numerosity tuning is affected by attention to the numerosity even when it was not shown (Figure 1). Each participant performed 18 or 19 runs in total.

To map numerosity-tuned responses in the brain, we used a pRF model (modeling tuned responses to the stimulus numerosities) combined with a GLM (responding to the timing of task targets. We defined five numerosity-tuned maps—NTO, NPO, NPC3, NPC2 and NPC1 (N: Numerosity, T: Temporal, P: Parietal, O: Occipital) (Harvey & Dumoulin, 2017). Then performed pairwise

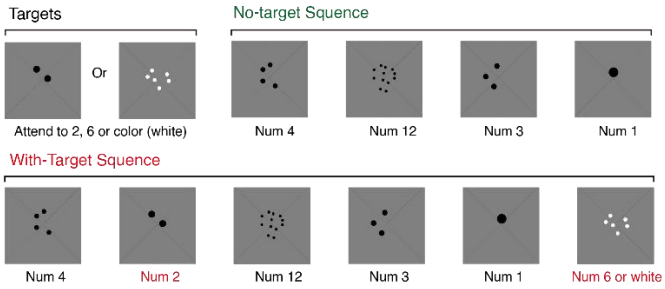

Figure 1: Experiment stimuli.

comparisons of preferred numerosities among the three attention conditions within these numerosity maps.

Results

First, we compared the mean preferred numerosity in each numerosity map the two attended numerosity conditions and the color baseline condition (Figure 2). Across all five maps, preferred numerosities were reduced when attending to low numerosity targets and increased when attending to high numerosity targets, compared to attending a non-numerical feature (color). This demonstrates that the preferred numerosities of numerosity-tuned neural populations are shifted toward the currently attended numerosity.

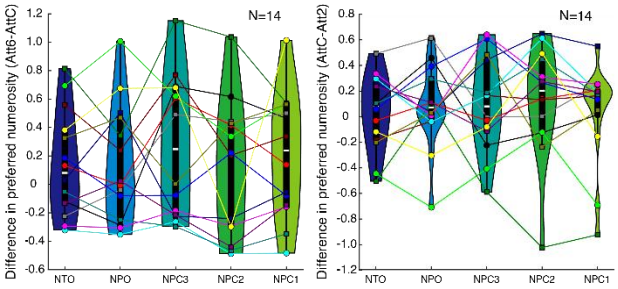

Figure 2: Mean preferred numerosity differences in numerosity-tuned maps. The left panel shows the difference in mean preferred numerosity between high and baseline conditions. The right panel shows this difference between baseline and low conditions.

Second, we asked whether this change in preferred numerosity depended on the relationship between the target numerosity and the baseline preferred numerosity of each recording site (voxel). We found that the change in preferred numerosity increased with the difference between the baseline and target numerosity (Figure 3). Indeed, voxels with preferred numerosities below the target typically increased their preferred numerosity, while voxels with preferred numerosities above the target typically decreased their preferred numerosity. As such, preferred numerosities were bidirectionally attracted toward the target, as seen for effects of attention on spatial response preferences.

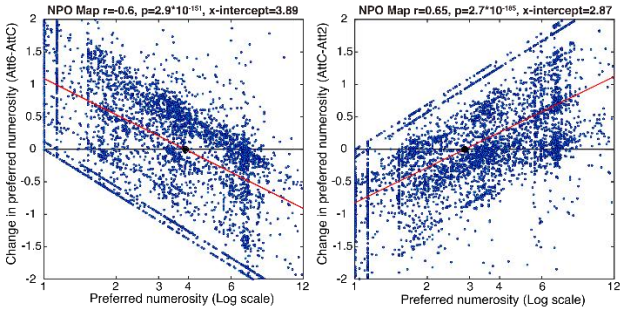

Figure 3: Within each numerosity map (here NPO) attention to specific target numerosities attracts individual voxels' preferred numerosities towards these targets. The left panel shows the difference in preferred numerosity between high and baseline

conditions. The right panel shows this difference between baseline and low conditions.

Discussion

The current study highlights two key points. First, numerical cognition is affected not only by low-level sensory input but also by high-level cognitive processes, such as goal-directed attention. Second, the effect of attention on numerosity processing depends on the difference between the attended numerosity and baseline preferred numerosity. This effect dynamically changes the numerosity preference according to the currently attended target.

Specifically, we found that the preferred numerosity of tuned neural populations shifts toward the numerosity that is currently attended. This bidirectional modulation suggests a flexible reallocation of numerosity representations based on task demands. These changes in numerosity preferences with attention to specific numerosities resemble effects of visual spatial attention on visual spatial response preferences (Klein et al., 2014), suggesting similar mechanisms of attention apply in sensory and cognitive processing alike.

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