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Numerical quantity affects time estimation in the suprasecond range

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HIGHLIGHTS

- Time estimation in the suprasecond range was influenced by numerosity information.
- The influence of numerosity on time estimation was observed only in females.
- Our study suggests a common representation for suprasecond intervals and numerosity.
- Degree of interconnectivity in the parietal cortex may explain the gender difference.

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ABSTRACT

Of stimuli differing in the magnitude of their numerical information, the one with the larger numerosity is perceived to last longer than that with the smaller numerosity. This numerosity–time interaction is proposed to be due to a shared neural representation for numerical magnitude and time intervals in the parietal cortex. Neuroimaging studies of temporal processing suggest that subsecond and suprasecond intervals could be mediated by distinct neural substrates. However, whether the numerosity–time interaction occurs independently of the time intervals used in the tasks remains unknown. Here we show that numerical information interacts with time estimation in the suprasecond range in females, but not in males. Our results suggest that the numerical magnitude and suprasecond intervals have shared representations in the human brain, but the associative strength between these dimensions might be different between males and females.

1. Introduction

Judgments of time intervals are often susceptible to interferences from seemingly irrelevant stimulus properties such as speed of motion [1], temporal frequency [9], size [17], luminance [23], stimulus sequence and repetition [7,18]. In addition to these simple features of stimuli, recent behavioral studies have shown that duration judgments are also influenced by irrelevant numerical magnitude information in the stimulus. Typically, a stimulus that contains information of larger numerosity is judged to last longer than a stimulus containing information of smaller numerosity. However, it has been pointed out that the numerosity–time interaction in categorical duration discrimination tasks (e.g., longer versus shorter judgment) [4,16,23] could solely be explained by a decision bias as a result of conflicting (or congruent) more-versus-less categorical information between time and numerosity dimensions [3,5,6] rather than distortion of subjective passage of time. To examine whether numerical information influences time estimation at the perceptual level, Chang et al. [3] used a time reproduction task that aimed to minimize the role of categorical decisions. The results showed that participants tended to estimate the larger numerical magnitude to last longer, which resulted in longer time reproduction. The authors suggested that this result reflected modulation of subjective passage of time by numerosity information at the perceptual level due to shared representations for time intervals and numerical magnitude, in line with A Theory Of Magnitude (ATOM) [21] suggesting a common neural representation for time, space and quantity in the intraparietal cortex (IPC).

Although Chang et al.'s study demonstrates that numerical magnitude influences time estimation, the generality of this phenomenon is unclear. For example, since the numerosity–time interaction with a time reproduction task has so far been tested only in the range of subsecond intervals (≤1 s), it is not known

Abbreviations: IPC, intraparietal cortex; ATOM, A Theory Of Magnitude.

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whether such interaction occurs also in the range of suprasecond intervals (>1 s). A growing body of neuroimaging studies of temporal processing suggests that temporal processing of subsecond and suprasecond intervals rely on partially overlapping but distinct neural networks [12,22]. These studies suggest that the occurrence of the numerosity–time interaction might depend on stimulus time intervals that carry numerical values.

In addition to the limited knowledge about time intervals, there is little information about possible gender differences in the numerosity–time interaction. The parietal cortex, where the general magnitude system is supposed to be located, has been reported to show structural differences between the sexes, and these findings were linked with sex differences in visuo-spatial performance [11]. Despite these findings, possible behavioral sex differences in the interactions between the magnitude dimensions consisting of the common metrics (i.e., time, space and quantity) have rarely been addressed. To our knowledge, there is only one behavioral study reporting sex differences in the spatial representation of numerosity [2]. Specifically, this study showed sex differences in the degree of spatial numerical association of response code (SNARC), numerical distance effect and linear acuity in number-line estimation. Authors concluded that these findings reflect sex differences either in the acuity of the representation or in the reliance on the spatial representation of number in the mental number-line. The study indicates a potential gender difference in the magnitude system. It is, however, unclear whether the interaction of other combinations of magnitude dimensions that form the common metrics in ATOM (i.e., interaction between numerosity and time, and between space and time) also show some behavioral sex differences.

In the present study, we examined whether the magnitude of numerical quantity influences suprasecond time estimation, and whether there are any sex differences in the degree of the interaction. To address these questions, we used a time reproduction task with non-symbolic numerical dot arrays.

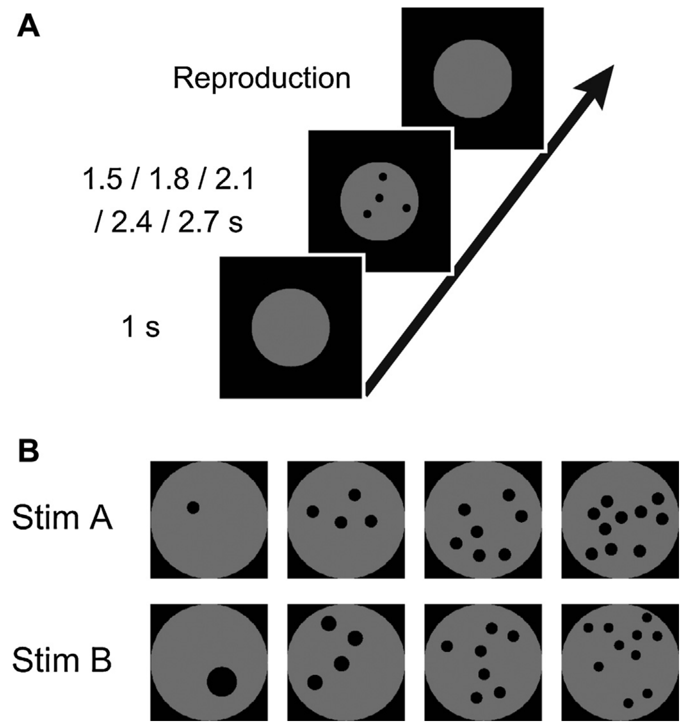

Fig. 1. Stimulus sequence and sets of dot arrays. (A) The stimulus sequence. After the presentation of a gray circle, a dot array was presented either for 1.5, 1.8, 2.1, 2.4 or 2.7 s. After the dot array stimulus had disappeared, participants reproduced the duration. (B) The visual dot arrays. Four different numerical magnitudes of dot arrays (1, 4, 7 and 10 dots) shown in two different formats were used.

2. Materials and methods

In total, 44 healthy, right-handed adults (22 males and 22 females) participated in the experiments. The male and female participants were randomly assigned into two groups (Groups A and B, each group consisting of 11 males and 11 females). There were no statistically significant differences between sexes with respect to age and years of education in both groups (Table S1). All participants gave a written informed consent. The experiments were approved by the Ethics Committee of the Hospital District of Helsinki and Uusimaa.

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We employed a time reproduction task involving numerosity–time interaction (Fig. 1A) [5]. The task was to estimate the duration of a visual stimulus containing numerical information (dot arrays) and to reproduce the duration by holding down the spacebar with the right index finger after the stimulus had disappeared. The dot arrays contained 1, 4, 7 or 10 dots and the stimulus durations were 1.5, 1.8, 2.1, 2.4 or 2.7 s. Group A received dot arrays in which the size of the dots was the same across the dot arrays (Fig. 1B, Stim A). Group B received dot arrays in which the total area of the dots in each dot array was adjusted to be equal across different numerical magnitudes (Fig. 1B, Stim B). These two different formats of dot arrays were used in order to control the factors of total area of the dots and size of each dot that correlated with the increasing numerical magnitude. Participants were instructed to fixate their eyes at the center of the screen, to ignore task irrelevant stimulus features (e.g., location of the dots), and not to "count" during the estimation and reproduction of the time intervals. Each participant completed 300 trials after performing 10 practice trials.

The dot arrays were generated by an automated program developed by Dehaene and colleagues [19]. The spatial positions of the dots placed within a gray circle (approximately 6°) were randomized. The stimuli were presented at the center of a cathode-ray-tube monitor running at 100 Hz. Participants put their chins on a chin rest positioned at a distance of 62 cm from the monitor. The computer keyboard was located between the monitor and the chin rest. Psychtoolbox (http://psychtoolbox.org) implemented on MATLAB software (Mathworks) was used to run the stimuli.

To quantify the degree of contribution of stimulus duration and numerosity to the reproduced duration, we computed non-parametric partial correlations between the reproduced duration and physical stimulus duration, and between the reproduced duration and numerical magnitude. In this analysis, we treated variables of non-interest (i.e., "numerical magnitude" for calculating partial correlations between the reproduced duration and physical stimulus duration, and "stimulus duration" for calculating partial correlations between the reproduced duration and numerical magnitude) as covariates. Non-parametric correlations were used because they allowed us to capture a monotonic increase (or decrease) even if the relationship was nonlinear. A positive effect of stimulus duration (i.e., a positive partial correlation between stimulus duration and reproduced duration) would indicate that the participant adjusted response durations according to the physical duration of the stimuli, and a positive effect of numerosity (i.e., a positive partial correlation between numerical magnitude and reproduced duration) would indicate that the reproduced durations were systematically increasing with increasing numerical magnitude. These values were individually computed, and then used as the input data in the statistical analysis. One sample