Relative Numerical Context Affects Temporal Processing

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Abstract

Several studies have reported that numerical magnitudes biases temporal judgments, i.e., large numerical magnitude, were perceived to last longer than small numerical magnitude. However, these predictions have been predominantly verified only when the large and small numerical magnitudes were presented in an intermixed fashion where numerical magnitudes varied randomly from trial to trial. We conducted two experiments (Blocked-magnitude and Mixed-Magnitude) using a temporal bisection paradigm to investigate whether numerical context affects temporal processing in a sub-second timescale. The numbers were presented with varying durations. Participants were asked to judge whether the presented durations were shorter or longer. The results suggest that the temporal judgments were affected when small and large numbers were randomly presented in an intermixed manner. However, such effects disappeared when the number magnitudes were presented separately. These results indicate the modulation of attention in number-time interaction, and such crosstalk may not require a generalized magnitude system.

Keywords: Cross-Modal Magnitude Interaction, Temporal Processing, ATOM

Introduction

Our daily life activities require us to process magnitudes from various domains. For example, a simple action like grabbing a pen from the desk requires subtle processing of information from space, time, and number domains. It has often been observed that the processing of one magnitude domain interferes with the processing of other magnitude dimensions. Such cross-dimensional magnitude interactions have been explained by *A Theory of Magnitude* (ATOM) (Walsh, 2003). According to ATOM, space, time, and number magnitudes are processed by a common magnitude system in the brain, thereby interacting with one another. ATOM asserts that this shared neural representation facilitates action coordination of task-relevant magnitudes (Walsh, 2003; Bueti & Walsh, 2009). When we want to grasp an object, for instance, magnitude is essential to perceive different dimensions of the object, such as distance, size, height, and so on. There are two distinct mechanisms for processing time, space, number, and other magnitude dimensions. In the first case, the various magnitudes can be analyzed, processed, and compared independently according to each individual metric. However, the second option is to consider a generalized magnitude system (ATOM), in which all magnitudes are processed similarly and according to a common metric system. According to ATOM, the later one is more efficient from the action selection point of view. Many behavioral and neuroimaging studies have substantiated ATOM's prediction advocating for a common magnitude system (Hubbard et al., 2005; Xuan et al., 2007; Bueti & Walsh, 2009; Srinivasan & Carey, 2010; Hayashi et al., 20013a; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016; Skagerlund, Karlsson & Träff, 2016). However, some studies did not support the idea of a common magnitude system and argued in favor of domain processing (Dormal, Seron, & Pesenti, 2006; Dormal, Andres, & Pesenti, 2008; Agrillo, Ranpura, & Butterworth, 2010; Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). Further, more recent studies have provided evidence against the common magnitude system and argued that such cross-dimensional magnitude interactions emerge from the cognitive factors like attention and memory (Vicario et al., 2008, Cai & Wang, 2014; Cai et al., 2018; Di Bono et al., 2020; Shukla & Bapi, 2021, b). Such inconsistent findings have raised a question on the existence of the common magnitude system. It is still an unsettled question and a matter of investigation. Therefore, the present paper examines whether there is a common magnitude system or the cross-dimension magnitude interactions are modulated by cognitive processes like attention and memory. More specifically, we investigate the influence of numerical magnitudes on the perceived duration.

Previous studies have shown that the task-irrelevant numerical magnitude modulates time processing. For example, the duration of a large numerical magnitude was overestimated, whereas the duration underestimation was observed for small numerical magnitudes (Oliveri et al., 2008; Chang et al. 2011; Cai & Wang, 2014; Hayashi et al., 2013b; Rammsayer & Verner, 2014; 2016). In an interesting study, Lu et al. (2009) suggested that number–time interaction can be modulated by contextual information presented with numerical magnitudes. Their study presented identical numerical stimuli with words indicating greater or

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lesser weight (kilogram or gram). They reported that the effect of numerical magnitude on time estimation appeared only when the higher unit of measurement (kilogram) was associated with the numbers. Their results suggested that the context can modulate the sense of number magnitude, affecting the number–time interaction.

Cross-dimensional magnitude interactions have been observed at both sub-second and supra-second timescales and argued for a common magnitude system (Hayashi et al., 20013b). On the contrary, many studies report an asymmetric interaction effect across different magnitudes (Dormal, Seron & Pesenti, 2006; Dormal & Pesenti, 2007; Bottini & Casasanto, 2010; Tsouli et al., 2019). For example, if a common magnitude system exists, the interaction should be bidirectional -- numerical magnitude should affect the processing of duration, and in the other direction, duration should also affect the processing of numbers. However, the lack of such a bidirectional influence of magnitudes has raised questions on the existence of a common magnitude system for space, time, and numbers. Further, few studies investigating the processing of numbers and time under dual-task conditions assume a common magnitude system and yield a similar influence on the processing of numbers and time. However, the findings suggest a differential influence of dual-task on the processing of numbers and time, indicating a lack of a common magnitude system (Young, Laura, & Cordes, 2013; Hamamouche et al., 2018). More recent studies have argued that attentional mechanisms may modulate such cross-magnitude interactions (Vicario et al., 2008; Di Bono et al., 2020; Shukla & Bapi, 2020, 2021).

Given the aforementioned findings, it is evident that the results reported for number-time interaction are mixed. In some of the studies, we could see a strong influence of numerical magnitude on temporal processing, but other findings do not follow ATOM's prediction. This raised a fundamental question about what is important in cross-dimensional magnitude interactions. Is it a numerical magnitude or the numerical context that provides the sense of magnitude? In the present paper, we specifically examine whether numerical magnitude (i.e., large and small) affects the perceived duration alone or the numerical context is required to give rise to cross-dimensional magnitude interactions. To test this, we design a study wherein we presented numerical magnitude (1 and 9) either in a blocked manner (1 and 9, presented in two separate blocks) or in a mixed order (1 and 9, presented randomly within same block). The idea here is to study the effect of magnitude and relative numerical context on duration judgements. According to ATOM, we process magnitudes of different kinds via a common magnitude system, then we should observe the number-time interaction independent of the type of presentation of the number (blocked vs intermixed).

Experiment-1: Blocked-Magnitude

In this experiment, we examine whether numerical magnitude on its own affects time processing. To study this question, we used a temporal bisection task wherein a numerical magnitude (small and large number) was presented in two separate blocks for varied durations. Participants were asked to judge the duration of the magnitude. We hypothesize that if numerical magnitude alone affects temporal processing, we should observe differential temporal processing for the two numerical magnitudes presented in separate blocks.

Method

Participants

Based on the pilot study, twenty-two right-handed university students (participants) (10 females and 12 males, age range = 20-30 years) were recruited. All participants had a normal or corrected-to-normal vision. They had given informed consent before the experiment. All the participants were paid for their participation. The institutional ethics committee approved the study.

Materials and Apparatus

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 19" Nokia CRT monitor (1024 x 768 resolutions) running at a 100 Hz frame rate. Participants were tested in a quiet room.

Stimulus

We used numbers, i.e., "1" and "9" as stimuli. These numbers were presented in black color against a white background. In this experiment, participants were trained on two anchor durations, 200ms and 800ms, and tested on seven probe durations of 200, 300, 400, 500, 600, 700, and 800ms. Each probe duration was repeated 10 times for each number. Therefore, each number was presented 70 times in a block and 140 trials in total across the two blocks.

Procedure

All the participants were taken to a dimly lit experimental room. They were asked to sit comfortably. The distance between the participants and the computer monitor was 57 cm. The instruction was given in both verbal and written format. In the *training phase*, participants received 10 trials of short anchor duration (i.e., 200ms) and 10 trials for long anchor duration (i.e., 800ms) along with the number "5" to understand what is meant by short and long durations. After the training phase, participants were given a feedback phase where the number "5" was randomly presented either for 200 or 800 ms duration. Participants were asked to identify whether the presented duration was long or short.

They were given feedback as ‘correct’ or ‘incorrect’ for their responses. In this phase, we ensured that participants performed with 95% accuracy. Once the participants reached the performance threshold, they were taken to the next phase, i.e., the testing phase. In the *testing phase*, participants were presented small number and a large number, i.e., “1” and “9” along with probe durations. In this experiment, the small and large numbers were presented in separate blocks. The participants were asked to judge whether the duration of the presented number was closer to small or the long anchor duration and were asked to register their response by pressing a designated key (left-arrow and right-arrow) on the keyboard. The key dedicated for the long and short responses were counterbalanced across participants. The numbers used in experiments were of 2° visual angle. To avoid any order effect, the order of the blocks was also counterbalanced across participants.

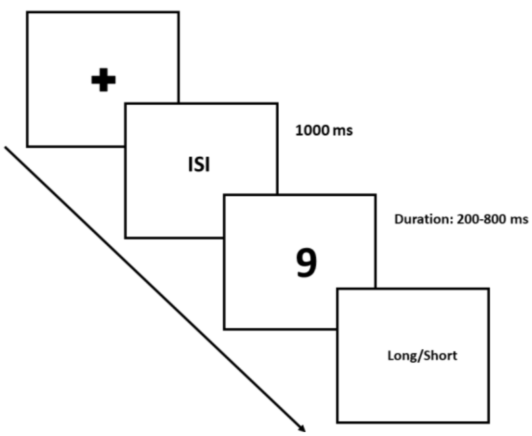

Figure-1: Illustration of the Blocked Task: each trial starts with the fixation cross, followed by an interstimulus interval of 1000ms. After the ISI, the numerical magnitude (either "1" or "9" depending on the block) was presented for a varied duration from 200-to 800 ms. Participants were required to judge the duration of the number.

Results

The data were recorded in terms of long and short responses. We estimated a bisection point (BP) for each numerical magnitude condition using a *logistic function*. The formula for the logistic function is $y = \frac{a}{(1+e)^{-k(x-x_c)}}$, where x_c is the x value of the sigmoid’s midpoint, a is the curve’s maximum value, and k is the steepness of the curve. The BP is the point at which 50% of the time participants would have perceived the presented duration to be closer to the short anchor and 50% of the time closer to the long anchor duration (Figure-2). The bisection point (BP) is also called the *point of subject equality* (PSE). Hereafter, we use PSE instead of BP. A higher PSE would be interpreted as an underestimation of duration and a lower PSE as an overestimation of duration.

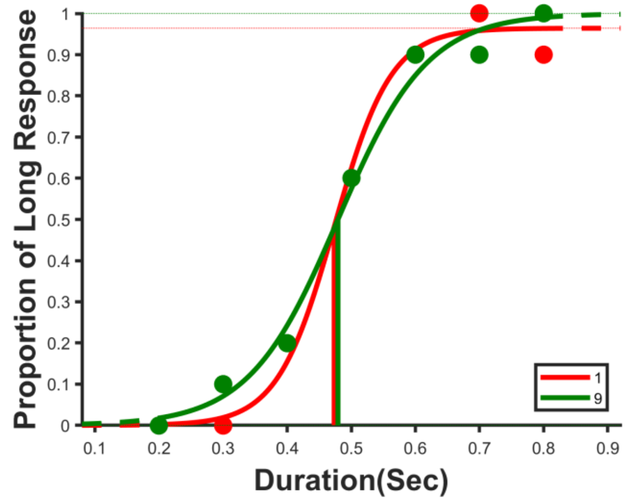

Figure-2: A Psychometric fit for the results of a representative participant from a blocked experiment wherein number “1” and “9” were presented in two separate blocks. The red color line represents number "1" and the green color represents number "9".

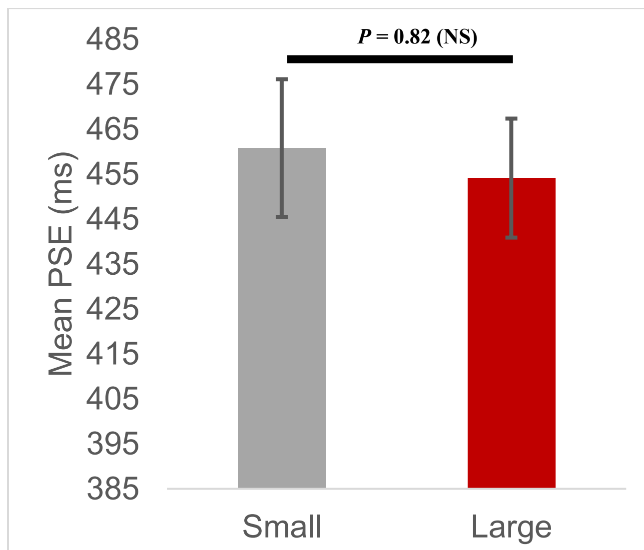

Figure-3: Mean PSE for small and large numerical magnitude conditions. The error bar represents the standard error.

To examine whether numerical magnitude by itself affects temporal processing, we calculated PSEs for small and large numerical magnitude for each participant and submitted them to paired t-test. The result of the paired t-test indicates that the PSEs between the two numerical magnitude conditions does not differ significantly from each other [t(21) = 0.228, p = 0.821, Cohen’s d=0.049], suggesting that the perceived duration for the small numerical magnitude (460.811 ms) did not differ from the large numerical magnitude (454.117 ms). Further, to test the magnitude of the null effect, we carried out a Bayesian paired t-test. The Bayes factor analysis yielded a value of B10 = 0.22. Considering that it is below 1, we can conclude that there is favorable evidence for rejecting the alternative hypothesis (in other words, the results are 4.54 times more likely to have occurred under the null model). The overall results suggest that the numerical magnitudes (small and large) did not modulate the perceived duration when presented in two separate blocks.

Experiment-2: Mixed-Magnitude

The null results of experiment-1 motivated us to conduct another experiment wherein we present the numerical magnitudes in an intermixed manner and see whether numerical magnitude affects perceived duration when the two numerical magnitudes are presented randomly in the same block.

Method

Participants

Based on the pilot study, twenty-three right-handed university students (participants) (9 females and 14 males, age range = 20-30 years) were recruited. All participants had a normal or corrected-to-normal vision. They gave informed consent before the experiment. All the participants were paid for their participation. The institutional ethics committee approved the study.

Materials and Apparatus

The stimuli were presented and controlled using E-Prime Standard-2.0 on a 19" Nokia CRT monitor (1024 x 768 resolutions) running at a 100 Hz frame rate. Participants were tested in a quiet room.

Stimulus

The durations and numerical magnitudes used in this experiment were identical to experiment-1.

Procedure

All the participants were taken to a dimly lit experimental room. They were asked to sit comfortably. The distance between the participants and the computer monitor was 57 cm. The instruction was given in both verbal and written format. In the training phase, participants received 10 trials of short anchor duration (i.e., 200ms) and 10 trials for long anchor duration (i.e., 800ms) along with the number "5" to understand short and long duration. After the training phase, participants were given a feedback phase where the number "5" was randomly presented either for 200 or 800 ms. Participants were asked to identify whether the presented duration was long or short. They were given feedback as correct or incorrect for their response. In this phase, we ensure that participants perform with 95% accuracy. Once the participants were reached this performance threshold, they were taken to the next phase, i.e., the testing phase. In the testing phase, participants were presented a small and a large number, i.e., "1" and "9" along with probe durations. Unlike in experiment-1, here the small and large numbers were presented randomly within the same block. Rest of the protocols were identical to experiment-1.

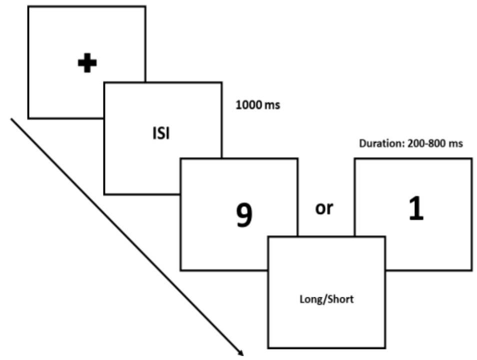

Figure-4: Illustration of the Mixed Task: each trial starts with the fixation cross, followed by an interstimulus interval of 1000ms. After the ISI, the numerical magnitude either "1" or "9" was presented randomly for a varied duration from 200 to 800 ms. Participants were required to judge the duration of the number.

Results

We estimated a *Bisection Point* (BP) for each numerical magnitude condition using a *logistic function*. (Figure-5). Hereafter, we use PSE instead of BP.

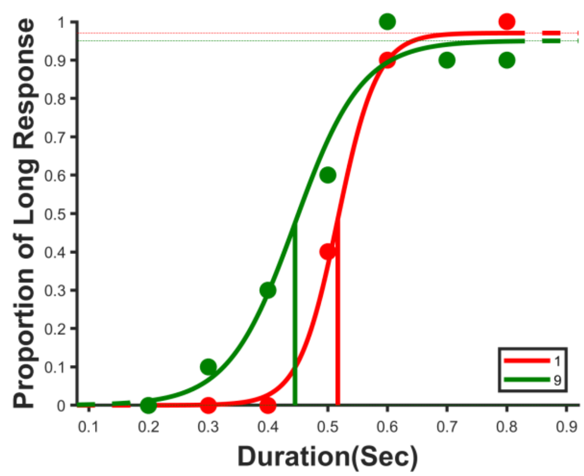

Figure-5: A Psychometric fit for the results of a representative participant from a mixed experiment wherein number "1" and "9" were presented randomly within the same block. The red color line represents number "1" and the green color represents number "9".

To examine whether numerical magnitude affects temporal processing when presented in an intermixed manner, we calculated PSEs for small and large numerical magnitudes for each participant and submitted them to paired t-test. The result of the paired t-test indicates that the PSEs between the two numerical magnitude conditions differ significantly from each other [$t(22) = 2.691$, $p = 0.013$, Cohen's $d = 0.561$], suggesting an underestimation of duration for the small numerical magnitude (470.488 ms) and a relative overestimation of duration for the large numerical magnitude (438.053 ms) (Figure-6).

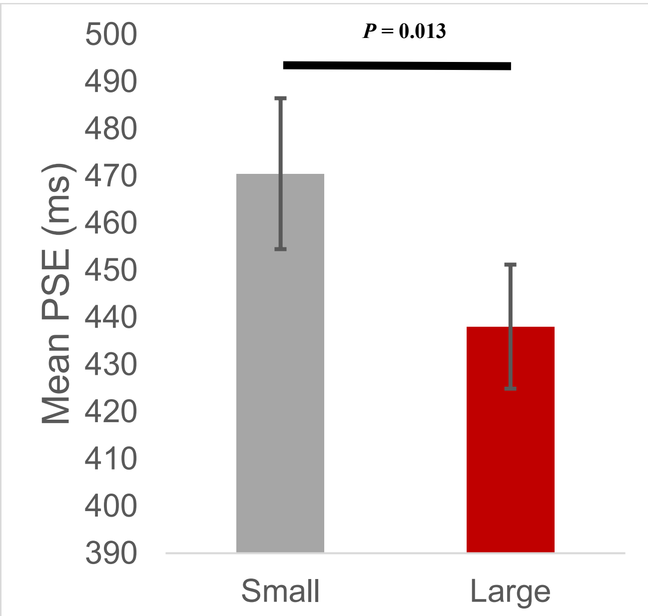

Figure-6: Mean PSE for small and large numerical magnitude conditions. The error bar represents the standard error.

Discussion

In the present study, we examined whether the numerical magnitude on its own affect temporal processing or the number-time interaction emerges from a numerical context. We used a temporal bisection task wherein we presented numerical magnitudes for varied durations, and participants were asked to judge whether the presented durations were long or short as compared to previously memorized short and long anchor durations. We hypothesized that if number and time share a common magnitude representation, the common magnitude system automatically engages whether the numerical magnitudes (numbers) are presented in individual blocks (experiment-1) or in intermixed in the same block (experiment-2). Our results from the two experiments suggest that the numerical magnitude affects temporal processing only when the number magnitudes are presented within the same block. No temporal processing differences were observed when the large and small numerical magnitudes were presented in two separate blocks. Previous studies investigating the influence of numerical magnitude on the processing of time have argued in favor of a common magnitude system and supported ATOM's predictions (Hubbard et al., 2005; Xuan et al., 2007; Bueti & Walsh, 2009; Srinivasan & Carey, 2010; Hayashi et al., 20013a; Cai & Connell, 2015; Schwiedrzik, Bernstein, & Melloni, 2016; Yamamoto, Sasaki, & Watanabe, 2016; Skagerlund, Karlsson & Träff, 20016). However, the findings of the present study seem interesting and point toward a relative numerical context effect. In other words, numerical magnitude affects temporal processing only when large and small numbers are presented in the same block.

Interestingly, the same numerical magnitudes (in fact, the same numbers 1 and 9) affect time perception differently in different experimental setups. The current findings replicate the number-time interaction (Experiment-2, see figure-6) and suggest that such cross-dimensional magnitude interactions may emerge from cognitive factors like attention. Further, the results also point out that the mere presentation of numerical magnitude may not lead to temporal bias. For example, the numerical magnitudes (large and small) when presented in a blocked manner do not lead to differential temporal processing (see experiment-1, figure-1). In contrast, the same numerical magnitudes (large and small) affect duration judgments when presented together, suggesting that the relative sense of magnitudes is crucial for cross-dimensional interactions. The findings from the two experiments indicate that the number and time magnitude may not be processed by a common magnitude system as posited in the ATOM framework. If these magnitudes required common processing mechanisms, then numerical magnitude would have affected temporal processing equally in both the experiments. Our present results indicate that a sense of numerical magnitude is crucial for cross-dimensional interactions. Presentation of numerical magnitude in separate blocks may not raise a relative sense of large and small numerical magnitudes. Thus, the number did not interact with temporal processing in the blocked experiment. However, the moment both the numbers were presented within the same block, it evoked the relative sense of magnitude. Thereby, the same numerical magnitudes but presented within the same block affected temporal processing and resulted in an overestimation of time for large magnitude trials and relative underestimation of time for small numerical trials. The present findings are consistent with the recent studies suggesting that numerical magnitude biases temporal processing and such bias may emerge from differential attentional mechanisms required for processing large and small magnitudes (Casarotti et al., 2007; Di Bono et al., 2020; Shukla & Bapi, 2020, 2021). Alternatively, it is possible that since the primary task is duration comparison, numbers are to be ignored. Incidentally, in the blocked experiment, the number might be truly irrelevant as the same number appears throughout the block, perceptual or attentional system might ignore it automatically. Whereas in the intermixed condition, the background is not stable, the numbers associated with durations keep changing between 1 and 9. So the spatial attentional processes might get engaged and connect this to the magnitude processing system (Fischer et al., 2003; Vicario et al., 2008).

The limitations of the present study could be the change in the luminance across the different experiments and magnitude conditions. Although we controlled the size of the numerals (1 and 9) used in this study, it could be possible that the shape of the numerals itself could potentially cause a change in the overall luminance across different conditions. Thus, future investigations should be carried out by controlling for the luminance explicitly and studying the number-time interactions.

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