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Big Time Is Not Always Long: Numerical Magnitude Automatically Affects Time Reproduction

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Abstract

To reproduce the duration of an event precisely, one needs to represent the temporal information without being influenced by other magnitude attributes (e.g., size) of the event. In the present study, however, task-irrelevant numerical magnitude automatically affected participants' reproduction of the duration of a stimulus. In Experiment 1, participants made key-press responses to reproduce the duration of numbers. Reproduced durations were shorter for small numbers (e.g., 1) than for large numbers (e.g., 9). In contrast, in Experiment 2, participants' reproductions of a standard duration were longer when their key-press response was accompanied by visual presentation of a small number than when it was accompanied by presentation of a large number. These results clearly demonstrate that number-time interference extends beyond simple mapping between stimulus categories and response alternatives. The findings support the notion that either a common magnitude representation or closely connected magnitude representations underlie numerical and temporal processing.

Keywords

time perception, number comprehension, cognitive processes, response bias

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Representing and processing time and quantity precisely are both critical to survival. The fact that animals and humans alike demonstrate innate abilities to understand information in these two domains indicates that these functions were present at an early stage of evolution and also are present early in human development (Buhusi & Meck, 2005; Feigenson, Dehaene, & Spelke, 2004). Studies have shown that temporal and numerical processing have comparable psychophysical functions in both rats (Meck & Church, 1983) and humans (Droit-Volet, Clement, & Fayol, 2003). Timing and numerical abilities also exhibit similar developmental trajectories (Brannon, Suanda, & Libertus, 2007; Feigenson, 2007; vanMarle & Wynn, 2006). These findings suggest that time and number computations are supported by common mechanisms or by separate mechanisms with similar characteristics.

A Stroop-like paradigm is typically employed to examine whether two tasks involve common or interacting stages of processing. For example, previous research has indicated that task-irrelevant information concerning numerical magnitude can affect the comparison of physical sizes of two numbers, and vice versa (Henik & Tzelgov, 1982; Kadosh et al., 2007; Schwarz & Ischebeck, 2003). Participants' judgment of both numerical and size magnitudes were more accurate and faster when the magnitude information in the two dimensions was congruent than when it was incongruent. Similar automatic interaction between numerical processing and action planning has also been reported (Andres, Davare, Pesenti, Olivier, & Seron, 2004; Lindemann, Abolafia, Girardi, & Bekkering, 2007). When people reached for an object or imagined this action, the magnitude of a task-irrelevant number printed on the object influenced their reaction time and grip aperture (Andres, Olivier, & Badets, 2008; Andres, Ostry, Nicol, & Paus, 2008; Chiou, Chang, Tzeng, & Wu, 2009).

In addition to influencing size computation and action planning, numerical information can affect the processing of time automatically. One pioneering study by Brown (1997) found that under dual-task conditions, mental arithmetic (but not rotor tracking or visual detection) was impaired by a concurrent temporal production task. More recent studies demonstrated that responses in a temporal comparison task were biased by task-irrelevant numbers of flashing dots in sequences (Dormal,

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Seron, & Pesenti, 2006), by numerical magnitudes embedded in stimuli (Oliveri et al., 2008; Vicario et al., 2008; Xuan, Zhang, He, & Chen, 2007), and by magnitude information in nonnumerical physical dimensions (Xuan et al., 2007). These studies generally found that participants tended to indicate that a stimulus was longer if it had larger task-irrelevant magnitude. These robust findings support the hypothesis that the processing of number and the processing of time are subserved by common or closely interacting representations.

Previous studies from the stimulus-response (S-R) compatibility paradigm have revealed that the compatibility of a magnitude attribute that is shared by the stimulus and the response can modulate response speed and accuracy (Grosjean & Mordkoff, 2001; Mattes, Leuthold, & Ulrich, 2002; Miller, 2006). In a study by Miller, Atkins, and Van Nes (2005), participants were asked to indicate whether they heard one or two tones by pressing a key either one or two times. Responses were faster with the compatible than with the incompatible S-R assignment. Also, Kunde and Stocker (2002) discovered that the congruency between task-irrelevant stimulus durations and key-press durations affected response times for color judgments. Such results highlight the automatic interaction between the perceptual and motor systems in computing magnitudes.

The findings from the S-R compatibility paradigm indicate that magnitude information in the perceptual domain and magnitude information in the motor domain interact. The findings from the Stroop-like interference paradigm further reveal the influence of numerical magnitude on temporal judgment. These results are consistent with the proposal that a common magnitude representation underlies the domains of quantity and time. However, these results can also be explained by simple mapping between stimulus categories (e.g., small numbers) and response alternatives (e.g., short durations). According to such reasoning, participants might simply associate one specific stimulus characteristic with one response label, without accessing the magnitude representation, while associating the opposite stimulus characteristic with the other response label. For example, Proctor and Cho (2006) have proposed the polarity correspondence principle, which suggests that in a binary classification task, participants tend to categorize stimuli into two polarities because of the task demand to choose one of two options in responding to each stimulus. Congruency of the polarity between the temporal and numerical dimensions might give rise to the number-time interference effect observed in previous studies.

In the present study, we used an interval reproduction task to examine whether numerical magnitude influences temporal processing in tasks that do not demand explicit binary classification decisions (e.g., temporal comparison). In Experiment 1, participants were required to reproduce a standard duration that was instantiated by the presentation of a small or large digit. If the reproduced durations were biased by the numerical magnitude of these digits, this result would not likely be due to the task demand of choosing one of two response options for each stimulus. Experiment 2 was designed to further eliminate the possibility that any apparent effect of numerical magnitude on interval reproduction is due to participants implicitly associating a nontemporal attribute of the to-be-reproduced interval to their response. Specifically, participants were required to reproduce the duration of a green dot by controlling the duration of a small or large digit. If an implicit association between numbers and reproduced intervals causes a magnitude effect, similar results would be expected regardless of whether the magnitude information appears in the standard stimulus (Experiment 1) or in the reproduction stimulus (Experiment 2). In contrast, if task-irrelevant magnitude exerts an automatic influence on the processing of temporal reproduction, reproduced durations expressed using a small number would be longer than necessary to compensate for the mental "compression" of the reproduction durations. That is, Experiments 1 and 2 would show ostensibly opposite effects of numerical magnitude on interval reproduction.

Method

Participants

All participants were healthy, right-handed college students from National Central University in Taiwan and had normal or corrected-to-normal vision. They received 100 New Taiwan dollars as compensation. All of them provided informed consent before the experiment. Sixteen and 24 students took part in Experiments 1 and 2, respectively.

Materials and designs

In the time reproduction task, a standard stimulus appeared on the screen for a standard duration. Participants then pressed a key to reproduce that standard duration. This key-press response was accompanied by a reproduction stimulus that was presented on the screen for the duration of the key press. Participants were instructed to make the reproduction duration as close to the standard duration as possible. In Experiment 1, the standard stimulus was one of four numerical stimuli (1, 2, 8, or 9; size ≈ 1.8° visual angle), and the reproduction stimulus was a green dot (size ≈ 0.7° visual angle). In Experiment 2, the standard stimulus was the green dot, and the reproduction stimulus was one of the four digits. In both experiments, participants were required to reproduce four standard durations: 300 ms, 450 ms, 600 ms, and 750 ms. The combination of the four digits and the four standard durations resulted in 16 conditions. There were 20 trials in each condition, for a total of 320 trials. These trials were separated into 10 blocks, each of which contained 2 trials in each condition.

Procedure

In both experiments, a trial started with a fixation cross that appeared at the center of the screen for 200 ms. After an

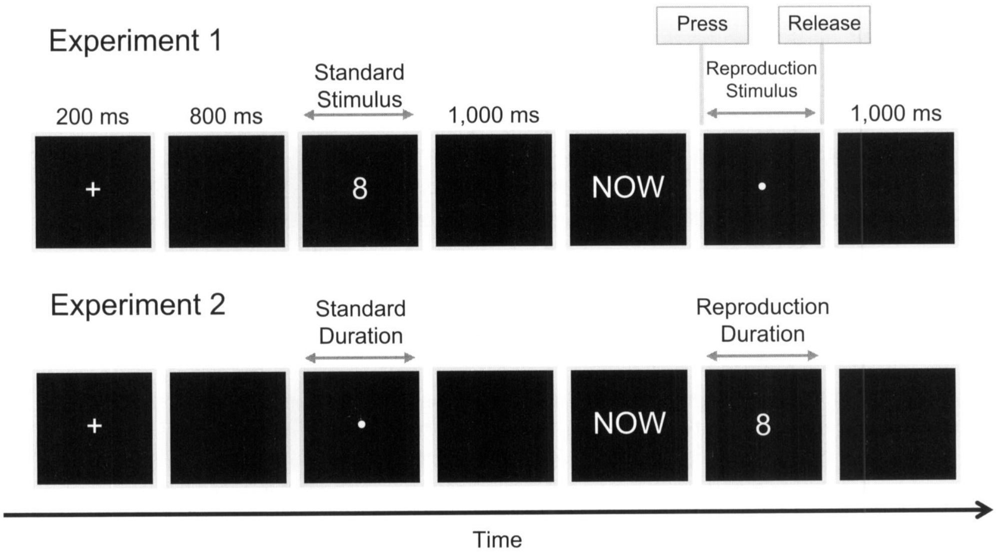

Fig. 1. Illustration of the trial sequence. Following a fixation cross, a standard stimulus (a numeral in Experiment 1, a green dot in Experiment 2) was presented for one of four standard durations. Participants were instructed that when the cue "NOW" appeared, they should press a key on a keypad to reproduce the duration of the standard stimulus. This key-press response was accompanied on-screen by a reproduction stimulus (a green dot in Experiment 1, a numeral in Experiment 2).

800-ms blank screen, the standard stimulus appeared for one of the standard durations. The standard stimulus was followed by a 1,000-ms blank screen. Next, the word "NOW" (about 3.3° in width and 1.1° in height) appeared as the cue to prompt participants' reproduction response. Participants were instructed to continuously press the "0" key on a digital keypad until the duration of the standard stimulus was reached. As soon as participants pressed the key, the cue word was replaced by the reproduction stimulus, which remained on the screen until participants released the key. Following the key press, there was a 1,000-ms blank screen before the next trial (see Fig. 1 for illustrations of the trial sequence).

Results and Discussion

Experiment 1

In Experiment 1, participants were required to reproduce the standard duration (300, 450, 600, or 750 ms) of a small (1 or 2) or large (8 or 9) number. All reproduction durations shorter than 100 ms or longer than 1,000 ms (2.13% of the trials) were removed from analysis. In addition, for each participant, all reproduction durations that were more than 2 standard deviations from that participant's mean reproduction duration for the corresponding condition (4.3% of the trials) were removed. Each participant's remaining reproduction durations were submitted to a one-way analysis of variance (ANOVA) with standard duration (300 ms, 450 ms, 600 ms, or 750 ms) as the independent variable. The lack of a significant main effect would imply an inability to follow the instruction to reproduce the standard duration. None of the participants were excluded on the basis of this criterion.

We also computed the coefficient of variation (CV) for each standard duration to validate task performance. The CVs decreased as the standard duration increased (see Table 1). Although such a pattern seems to violate the scalar property of timing (Gibbon, 1977), similar results have been repeatedly reported in the literature on temporal reproduction tasks, especially for testing durations in the range from milliseconds to seconds (Lewis & Miall, 2009; Wearden, 2003; Wearden &

Table 1. The Coefficient of Variation for Each Standard Duration in Experiments 1 and 2

	Standard duration			
Experiment	300 ms	450 ms	600 ms	750 ms
Experiment 1	0.24 (0.07)	0.21 (0.06)	0.19 (0.05)	0.17 (0.04)
Experiment 2	0.23 (0.06)	0.20 (0.07)	0.17 (0.05)	0.16 (0.04)

Note: Standard deviations are given in parentheses.

Lejeune, 2008). Given that participants reproduced longer durations when the standard durations were longer, we believe that the participants followed the instructions and that their responses are valid, despite the violation of the scalar property.

The reproduction durations from all 16 participants were analyzed with a 2 (numerical magnitude: small or large) × 4 (standard duration: 300 ms, 450 ms, 600 ms, or 750 ms) ANOVA. The results revealed a highly significant main effect of standard duration, $F(3, 45) = 122.38$, $p < .001$, $\eta^2 = .89$, which indicated that participants' reproduction durations were proportional to the standard duration (see Fig. 2). Of critical theoretical interest, the main effect of numerical magnitude was also significant, $F(1, 15) = 5.87$, $p = .029$, $\eta^2 = .28$. Reproduction durations were larger when the standard stimulus was a large number ($M = 523$ ms, $SE = 21$ ms) than when the standard stimulus was a small number ($M = 513$, $SE = 20$ ms). The interaction between numerical magnitude and standard duration was not significant, $F(3, 45) = 0.9$, $p = .45$, $\eta^2 = .06$.

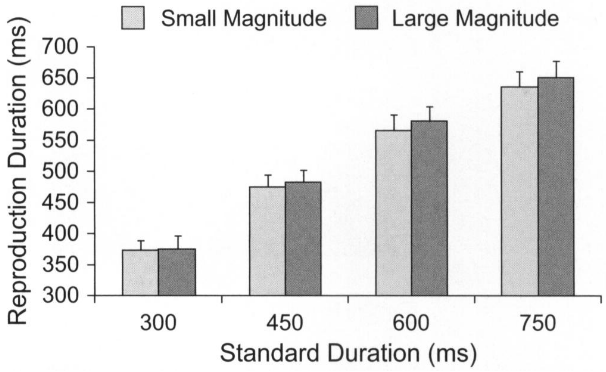

Fig. 2. Results from Experiment 1: mean reproduction duration as a function of duration and numerical magnitude (small: 1 and 2; large: 8 and 9) of the standard stimulus. Error bars represent standard errors in each condition.

Experiment 1 clearly demonstrated that task-irrelevant quantity information affected reproduced durations, even though no selection between two response alternatives was required. These results cannot be accounted for by simple mapping between stimulus attributes and response options or by the polarity correspondence principle (Proctor & Cho, 2006). However, we cannot completely rule out the possibility that participants implicitly associated large numbers with temporally long key presses, and therefore made longer key-press responses following large than following small numbers. Similarly, participants might have associated small numbers with temporally short key presses without accessing magnitude representations of the numbers. If the results were due to such associations, the same results should be obtained regardless of whether the nontemporal magnitude information is presented in the standard or the reproduction stimulus. Experiment 2 investigated this possibility.

Experiment 2

In Experiment 2, we further removed nontemporal magnitude information from the standard stimulus, to determine whether the results obtained in Experiment 1 were simply caused by implicit S-R mapping. The green dot was used as the standard stimulus, and the four numbers were used as reproduction stimuli. Adopting the same criteria as in Experiment 1, we identified 4.2% of trials as outliers and removed them from further analyses. One participant was excluded because the standard duration did not have a significant main effect on his reproduction durations ($p = .45$). As in Experiment 1, CVs decreased as the standard duration increased (see Table 1).

A 2 (numerical magnitude: small or large) × 4 (standard duration: 300 ms, 450 ms, 600 ms, or 750 ms) ANOVA was performed on the remaining data. The main effect of standard duration was highly significant, $F(3, 66) = 119.29$, $p < .001$, $\eta^2 = .84$; participants' reproduction durations were longer when the standard duration was longer (see Fig. 3). The main effect of numerical magnitude was also significant, $F(1, 22) = 5.58$, $p = .03$, $\eta^2 = .20$. In sharp contrast with the results of Experiment 1, however, reproduction durations that were accompanied by a small number ($M = 485$ ms, $SE = 15$ ms) were longer than those accompanied by a large number ($M = 480$ ms, $SE = 14$ ms). The interaction between standard duration and numerical magnitude was not significant, $F(3, 66) = 0.61$, $p = .61$, $\eta^2 = .03$.

The ostensibly opposite effect of numerical magnitude on the reproduction durations in Experiment 2 clearly rules out the possibility that the results in Experiments 1 and 2 were caused by simple, rigid mapping between the numbers and the durations of key presses. Instead, the results suggest that task-irrelevant magnitude exerts an automatic influence on the processing of temporal reproduction. In Experiment 2, when reproduction responses were accompanied by a small number, participants' intended reproduction durations were subjectively shortened relative to the standard duration because of the bias associated with the small magnitude. The duration of the reproduction response was lengthened to compensate for the mentally compressed reproduction interval. In contrast,

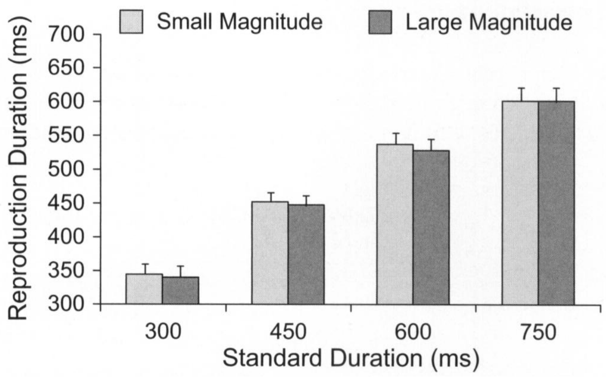

Fig. 3. Results from Experiment 2: mean reproduction duration as a function of the duration of the standard stimulus and the numerical magnitude (small: 1 and 2; large: 8 and 9) of the reproduction stimulus. Error bars represent standard errors in each condition.

when reproduction responses were accompanied by a large number, participants' intended reproduction durations were subjectively lengthened relative to the standard duration because of the bias associated with the large magnitude. A shorter duration was reproduced to compensate for the mentally stretched reproduction interval.

General Discussion

This study demonstrated the automatic effect of numerical magnitude on temporal reproduction. This effect was robustly demonstrated even though the task did not demand selection between two response alternatives. The results cannot be easily accounted for by rigid S-R mapping or by the polarity correspondence principle (Proctor & Cho, 2006). Numbers with small magnitude were not always associated with short reproduction durations, and numbers with large magnitude were not always associated with long reproduction durations; our two experiments clearly revealed contrasting patterns depending on whether the information on numerical magnitude was conveyed by the to-be-reproduced or the reproduced duration. Such findings are strong evidence for the involvement of magnitude representation in the interaction between numerical and temporal processing.

One potential explanation for our findings is that task-irrelevant magnitude information embedded in numbers automatically and immediately affects the encoding of a duration. According to this explanation, in Experiment 1, participants subjectively perceived the standard duration to be shorter when the standard duration was instantiated by a small number than when it was instantiated by a large number; hence, they reproduced shorter durations when the standard duration was instantiated by a small number. In Experiment 2, immediately after perceiving the standard duration of a magnitude-free green dot, participants subjectively shortened a reproduction duration that was accompanied by a small number, compensating for this mental compression by reproducing a longer duration.

This account of our findings is consistent with the mode-control model proposed by Meck and Church (1983), which postulates that the same encoding mechanism underlies quantity and time processing. A similar model with an extended scope, a theory of magnitude (ATOM), was proposed by Walsh (2003). According to ATOM, time, space, and quantity processing rely on a common magnitude representation, and these three systems share information-processing resources and behavioral goals. Recent empirical work has demonstrated a close connection between representations of space and number (Hubbard, Piazza, Pinel, & Dehaene, 2005; Hung, Hung, Tzeng, & Wu, 2008) and between representations of space and time (Vicario et al., 2008), especially when the task involves action planning and execution (e.g., Chiou et al., 2009; Chiou, Wu, Tzeng, Hung, & Chang, in press). The ATOM model further postulates that time and quantity estimation operate on a partly shared accumulation mechanism, which corresponds to the encoding component in the scalar timing model (Gibbon, Church, & Meck, 1984).

One recent electrophysiological study (Xuan, Chen, He, & Zhang, 2009) supports the claim that numerical magnitude affects temporal perception at a relatively early stage. The contingent negative variation (CNV), one component of event-related potentials, reflects the subjective duration of a temporal event (Macar & Vidal, 2004). In a time-comparison task, Xuan et al. showed that the amplitude of the CNV was modulated by numerical quantity even when participants were instructed to perform temporal but not magnitude judgment.

Although the present findings might result from a common magnitude representation underlying numerical and temporal processing, they could also arise from distinct but strongly interacting representations of quantity and time. It is possible that small and large numbers automatically activate the representation of short and long durations, respectively, and that such activation can bias reproduction responses. In Experiment 1, reproduction durations were shorter when the standard duration was instantiated by a small number than when it was instantiated by a large number. In Experiment 2, in which the numbers appeared when reproduction responses were initiated, the opposite pattern was found. To account for this reversal, we reason that a small number activated the representation of a short duration, thereby subjectively compressing the response interval. To cancel out this effect, participants made longer key-press responses. Similarly, the appearance of a large number activated the representation of a long duration, and participants made shorter key-press responses to compensate for this effect.

An association between numerical magnitude and the speed of response initiation was demonstrated in a recent study by Kiesel and Vierck (2009). They found that parity judgments on a small number were initiated more quickly when response durations were short than when they were long, whereas the same judgments on a large number showed the opposite pattern. Further research is needed to determine whether the effect of numerical magnitude on temporal reproduction occurs at the stage of encoding temporal duration or at the stage of initiating the reproduction response. It is also possible and likely that the effect takes place at both stages.

In the present study, the reproduction response immediately triggered the presentation of a visual stimulus on the screen. Thus, our task resembles the response-effect, or action-effect, paradigm (Kunde, 2001). Kunde found that response time was longer if the response and the elicited stimulus were incongruent as regards a common attribute (e.g., spatial position) than if they were congruent. It should be noted that the consequence of a response was always predictable in Kunde's paradigm. In Experiment 2 of our study, however, the reproduction response was orthogonal to the manipulation of numbers. Because no anticipation of numerical magnitude could be formed before the reproduction response, it is unlikely that the observed interaction resulted from interference between action planning or execution and anticipation of the action's outcome.

Our results not only converge with recent findings in demonstrating a close relationship between numerical and temporal processing, but also provide strong evidence that the effect of quantity magnitude on temporal processing does not arise from simple, rigid mapping between numbers and certain responses, but rather arises from the influence of numerical magnitude on temporal processing. Further research is needed to determine whether the interaction between temporal and numerical processing results from a common magnitude representation or two separate but closely connected mechanisms. Future neuroimaging studies with superior temporal resolution might shed light on the precise dynamics of the interaction between the domains of time and numbers. One recent study (Crollen, Castronovo, & Seron, 2011) found underestimation when participants selected a (symbolic) number to indicate their perception of nonsymbolic numerosity. In contrast, when they used nonsymbolic stimuli to reproduce the quantity of a symbolic number, they tended to overestimate the amount. It is also worth exploring whether nonsymbolic numerosity modulates temporal processing in a manner similar to the way in which symbolic numerosity modulated temporal processing in the present study.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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