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The distance effect on discrimination ability and response bias during magnitude comparison in a go/no-go task

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Abstract
The distance effect is the change in the performance during numerical magnitude comparison, depending on the numerical distance between the compared numbers (Moyer & Landauer, *Nature, 215*[5109], 1519–1520, 1967). This effect is generally accepted as evidence for the mental number line (MNL) hypothesis, which proposes that the mental representation of the numbers align in an increasing linear (or monotone) order. The majority of studies investigating the distance effect are focused on the reaction time (RT) findings, which show slower responses for closer numbers. In the present study, we examined the distance effect by applying signal detection theory (SDT) to a magnitude comparison task. We aimed to reveal whether discrimination ability and the response bias measures were affected by the location of numbers on the MNL. To accomplish this, we developed a magnitude comparison task using a go/no-go procedure in which participants performed a magnitude comparison based on a reference number (i.e., 5). Results revealed a substantial distance effect in both sensitivity and response bias measures—a better discrimination performance for far numbers, and a larger response bias for close numbers. In addition, an RT distribution analysis revealed that the distance effect seems to originate mainly from slower responses. Based on the current data, we suggest that sensitivity and response bias measures could offer comprehensive information in the understanding of number-based decisions.

Keywords Mental number line · Distance effect · Magnitude comparison · Signal detection theory · Go/no-go task

Numerosity is a substantial concept in our quantity-related interactions with the environment. Humans can grasp the numerical system of the external world by using their inherent understanding of the numerical concept. Moyer and Landauer's (1967) demonstration of mental number storage resembling physical continua can be considered as the first evidence of such inherence. In essence, their evidence revealed that the reaction time (RT) for comparing the magnitudes of two presented digits decreased as the numerical distance between them increased. This effect was later called the numerical (or symbolic) distance effect (Dehaene et al., 1990; Moyer & Bayer, 1976).

Along with magnitude comparison, the distance effect was observed in various experimental tasks, such as the same–different judgement (van Opstal & Verguts, 2011), matching task (Goldfarb et al., 2011), and priming paradigm (Gabay et al., 2013). The robustness of the effect has been consistently exhibited by its extension to letters (van Opstal et al., 2008), dots (Sasanguie et al., 2011), pictures and names of animals and objects (Paivio, 1975), pitches (Cohen Kadosh et al., 2008), and social status (Chiao et al., 2004). Consequently, the distance effect gained a prominent place in studies on numerical and nonnumerical representations.

The most common interpretation of the distance effect is the mental number line (MNL) hypothesis (Dehaene et al., 1990). The MNL hypothesis proposes that numbers align on a linear (or monotone) order, on which smaller numbers are located on the left in our mental representation, and larger numbers on the right. According to the common explanation of the distance effect, activation strength of each number on the MNL can be represented as a Gaussian distribution function around the true location of that number, and this induces overlapping representations with the neighboring numbers (e.g., Basso Moro et al., 2018; Cohen Kadosh et al., 2005; Kaufmann et al., 2005). These overlapping representations create a co-activation process. A given magnitude activates its own representation as well as the representation of

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nearby numbers. Therefore, participants require additional time to gather more fine-grained information during magnitude comparison of close numbers. While this view proposes an explanation for the slower responses of close numbers during magnitude comparison, overlapping curves of close numbers might also interfere with the selection of the correct response.

Correct responses were examined in several studies along with RT, to examine the numerical distance effect by using the diffusion (or random walk) model. The model reveals how accuracy and RT are related to each other, and how experimental conditions differentially affect them. Studies using the diffusion model parameters in order to investigate distance effect revealed detailed information about the process of number-based decisions (Buckley & Gillman, 1974; Milosavljevic et al., 2011; Poltrock, 1989; Schwarz, 2001; Schwarz & Ischebeck, 2003; Sigman & Dehaene, 2005; Smith & Mewhort, 1998). Similar to the diffusion model, signal detection theory (SDT) uses parameters that reveal the underlying mechanism of a noisy decision process (Macmillan & Creelman, 2005), and can also offer valuable information for number-related decisions. For example, Reike and Schwarz (2017) explored their findings within the framework of response bias and sensitivity measures when participants judged the physical size of the digits. They revealed higher sensitivity occurred when the physical size and the numerical magnitude of the digit was congruent. On the other hand, researchers proposed that response bias, to some extent, influences the way in which participants compare the physical size of digits. As Reike and Schwarz (2017) revealed, applying SDT to number-related responses provides an extensive view about the origin and nature of participants' responses based on bias and sensitivity accounts. Correspondingly, we hypothesized that examining participants' responses during magnitude comparison using the SDT approach may contribute to understanding of whether the location of numbers on the MNL affect their decision variable.

Therefore, in the present study, we developed a magnitude comparison task by using a go/no-go procedure, and asked participants to respond or not based on the magnitude of each presented number. According to the activation strength view, we expected that overlapping representations of close numbers might create interference in the magnitude comparison task, and decrease discrimination ability. Furthermore, because close numbers have strong connections based on their location on the MNL, a response bias is more likely. In addition to the SDT analysis, we also performed a reaction time distribution analysis (see Ratcliff, 1979, for a detailed explanation) in order to reveal how different processing speeds during a numerical go/no-go task would influence the distance effect. Based on the previous studies suggesting that the spatial coding of the stimuli may not occur during fast responses (see Ansorge, 2003; Mapelli et al., 2003; Sellaro et al., 2014), we examined the strength of the distance effect in relation to differences among participants' processing speeds.

Method

Participants

Forty students from Izmir University of Economics volunteered (24 females, ages 19–34 years; $M = 24.75$ years, $SD = 3.77$). In order to determine the adequacy of the sample size, a power analysis was applied by using PANGEA (Power ANalysis for GEneral Anova designs, v0.2; Westfall, 2016). The analysis showed that, with a medium effect size ($d = .60$), the current experimental design provides a power > .99 with 40 participants. Participants were all right-handed and had normal or corrected-to-normal vision. None reported a prior history of neurological/psychological disorder or were under medication during the experimental session, and all provided written informed consent.

Apparatus and stimuli

All numbers from 1 to 9, except 5, were used as stimuli and presented in black on a white background (Helvetica 55 font) from the center of the Acer V193WBB 19-inch LCD with a 1,440 × 900 resolution and a refresh rate of 75 Hz. Stimuli were categorized as close (3, 4, 6, and 7) and far (1, 2, 8, and 9) based on their distance to the number 5. The stimulus presentation program was written in MATLAB R2016a (The MathWorks Inc., Natick, MA, USA) using the Psychtoolbox on TechnoPC 3.3Ghz/1GB VGA computer. Responses were obtained with a QWERTY keyboard.

Procedure

Participants were tested individually in a dimly lit and sound-isolated experimental chamber, seated at a distance of approximately 45 cm from the computer screen. Numbers were categorized as close (small: 3 and 4; large: 6 and 7) and far (small: 1 and 2; large: 8 and 9). From each number group—close and small, close and large, far and small, and far and large—eight numbers were randomly selected. The go/no-go task consisted of baseline-go (which includes 100% go trials) and go/no-go conditions (which includes 50% go and 50% no-go trials), which constitutes a block. For both conditions, 32 numbers were presented in a randomized order, resulting in 64 stimuli in a single block. In total, the participants took six blocks. The experimental sessions started with a baseline-go condition, followed by a go/no-go condition. Before each condition, participants were given instructions about the task requirements, with accompanying visual examples. Therefore, in each block, instructions for both conditions were provided. The blocks consisted of the following sequence of events: First, a black fixation square (17 × 17 mm) appeared in the center for 1,000 ms, followed by a stimulus for 500 ms, then an interstimulus interval (ISI) for 500 ms. Hence, participants were given a window of 1,000 ms from the onset of the number to respond. In the baseline-go condition, for all presented stimuli, participants were required to press the space bar with their right index finger as quickly as possible without making mistakes (see Fig. 1a). The purpose of the baseline-go condition was to bring participants' performance to a baseline level before each go/no-go condition (Fishburn et al., 2019; Miao et al., 2017; Monden et al., 2015), and this was regarded as a sensorimotor control condition. In the go/no-go condition, half of the participants were instructed to press the space bar with their right index finger as quickly as possible without making mistakes when the stimulus was larger than 5 (go trials), and not when smaller than 5 (no-go trials; see Fig. 1b). The other half were asked to do the opposite, and given the corresponding instruction (i.e., press when smaller than 5 [go trials], and not when larger [no-go trials]; see Fig. 1c).

Results

In all analyses, only trials in the go/no-go condition were analyzed. Performance measures of all close and far conditions for both groups (press large, press small) on the go/no-go task are presented in Table 1. In order to check for any effect of the different instructions, the instruction (press large, press small) was added as a factor in all analyses.

For investigating whether there was a speed–accuracy trade-off between conditions, we performed correlation analyses (Schulz et al., 2007; Waring et al., 2019). There was no significant correlation between the commission error (responding to no-go trials) rate and RT of correct go trials, and thus no evidence of a possible speed–accuracy trade-off in any of the conditions (see Supplementary Material Table S1).

Signal detection analysis

Data preparation Signal detection parameters were calculated based on the methods explained by Macmillan and Creelman (2005) and Stanislaw and Todorov (1999). Accordingly, responses to go trials were correct and recorded as a hit, while responses to no-go trials were incorrect and recorded as a false alarm. Due to the straightforward nature of the task, performances were high, and therefore 78.75% of the hits and 30% of the false alarms ended up in perfect scores (see Supplementary Material Table S2 and Table S3, for the frequencies), which prevents the calculation of the SDT measures. This issue was addressed by using the loglinear approach and calculating the nonparametric SDT measures. Loglinear approach involves adding 0.5 to all the observed hit and false-alarm numbers, while adding 1 to both signal and noise trial numbers while calculating the hit and false-alarm rates (Brown & White, 2005; Hautus, 1995; Macmillan & Creelman, 2005; Stanislaw & Todorov, 1999; Verde et al., 2006). Hit rates were obtained from the number of hits (plus 0.5) over the total number of go trials (plus 1), and false-alarm rates were obtained from the number of false alarms (plus 0.5) over the total number of no-go trials (plus 1). After calculation of the corrected hit and false- alarm rates (see Supplementary Material Table S4, for the descriptive statistics), the nonparametric measures of sensitivity (A') and response bias (Grier's B'') were obtained (Macmillan & Creelman, 2005). The possible values of A' range between 0 and 1, in which the values below 0.5 indicate a sampling error or response confusion, while the value of 0.5 indicates undistinguished signal and noise trials, and the value of 1 shows a perfect performance (Stanislaw & Todorov, 1999). The possible values of B'' range between −1 and 1, in which the value of 0 indicates no response bias, negative values yes-response bias, and positive values no-response bias (Stanislaw & Todorov, 1999). In the current study, the sensitivity parameter was used for showing whether participants' performance in discrimination of signal and noise trials depended on the distance between the numbers. The response bias parameter was used to show whether the participants show a tendency to respond with a bias, in any direction, for either of the distance categories.

Sensitivity (A') Sensitivity parameter was subjected to an analysis of variance (ANOVA), with instruction (press large, press small) as a between-participants factor, and distance category (close, far) as a within-participants factor. Results for A' yielded a significant main effect of distance, $F(1, 38) = 34.19$, $\eta_p^2 = .474$, $p < .001$. Far numbers ($M = .95$) were better discriminated than close numbers ($M = .92$; see Fig. 2, left panel). There were no main effects of the instruction and interaction effect, Fs $< .52$, ps $> .47$ (see Supplementary Material Table S5 and Table S6).

Response bias (B'') Response bias parameter was subjected to an ANOVA, with instruction (press large, press small) as a between-participants factor, and distance category (close, far) as a within-participants factor. Results for B'' yielded a significant main effect of distance, $F(1, 38) = 10.32$, $\eta_p^2 = .214$, $p < .01$. Participants had a larger bias for responding to close numbers ($M = -.44$) than to far numbers ($M = -.24$; see Fig. 2, right panel). There were no main effects of the instruction or interaction effect for response bias measures, Fs < 3.41, ps $> .07$ (see Supplementary Material Table S7 and Table S8).

Reaction time (RT) distribution analysis

Incorrect go trials (1.54 %) were excluded from the RT analyses. All RT values were between 200 ms and 1,000 ms. In order to reveal the effect of different processing speeds on the distance effect, we applied a distribution analysis of RTs (Ratcliff, 1979). RT distribution analysis is preferable to simply taking each participant's mean of the RT distribution, and is highly recommended based on the ex-Gaussian distribution

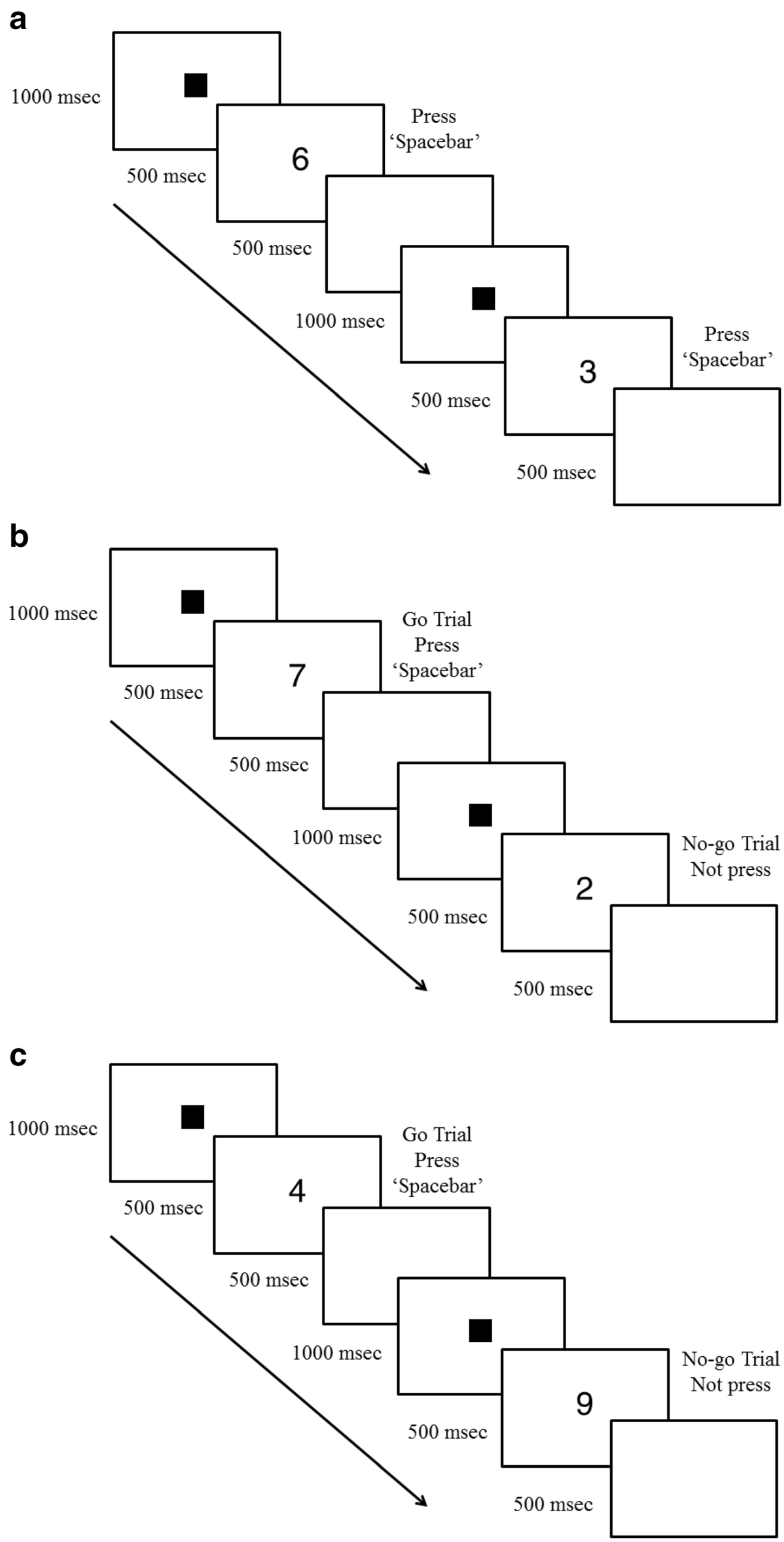

Fig. 1 Schematic illustration of sequence of events in the experiment. All participants took baseline-go condition and were instructed to press the space bar for all numbers (**a**). In the go/no-go condition, half the participants were instructed to press the space bar when the number was larger than 5 (**b**); and the other half, when the number was smaller than 5 (**c**)

Table 1 Descriptive statistics for performance measures in the go/ no-go task

	Press small				Press large			
	Close		Far		Close		Far	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Commission (%)	5.21	0.78	2.08	0.48	4.06	0.87	1.46	0.37
Omission (%)	0.31	0.17	0.31	0.17	0.83	0.28	0.42	0.19
Sensitivity (*A′*)	0.91	0.01	0.95	0.01	0.92	0.01	0.95	0.01
Bias (Grier's *B″*)	−0.54	0.07	−0.29	0.06	−0.35	0.07	−0.20	0.08
RT (Go trials) (ms)	426	10.33	396	12.98	438	4.15	422	12.98

nature of the RT data (Ratcliff, 1979; Whelan, 2008) and commonly used in numerical cognition studies (Gevers et al., 2006; Sellaro et al., 2014). For this analysis, correct RTs over all go trials in the go/no-go condition for each participant were ranked from fastest to slowest for instructions and distance categories. Each RT distribution was divided into 5 quantile bins. These RT results were then subjected to an ANOVA, with instruction (press large, press small) as a between-participants factor, and distance category (close, far) and bin (bin 1, bin 2, bin 3, bin 4 and bin 5) as within-participants factors. For the main effect of bin and the interaction effect of distance and bin, Greenhouse–Geisser-correction was applied, $\chi^2(9) = 243.84$, $p < .001$, $e = .30$; $\chi^2(9) = 132.75$, $p < .001$, $e = .38$, respectively. Results revealed a significant distance effect, $F(1, 38) = 77.50$, $\eta_p^2 = .671$, $p < .001$. Faster responses were found for far numbers ($M = 409$ ms) than for close numbers ($M = 432$ ms). The main effect of the bin was also significant, $F(1.19, 45.20) = 367.19$, $\eta_p^2 = .906$, $p < .001$. Two-way interaction of instruction and distance category was significant, $F(1, 38) = 7.11$, $\eta_p^2 = .158$, $p = .011$. Simple effect analysis revealed a larger RT difference between close and far numbers in the press-small condition (426 ms vs. 396 ms, respectively), $F(1, 38) = 65.77$, $p < .001$, than in the press-large condition (438 ms vs. 422 ms, respectively), $F(1, 38) = 18.84$, $p < .001$ (see Fig. 3). Most importantly, the two-way interaction of distance category and bin was significant, $F(1.51, 57.42) = 29.88$, $\eta_p^2 = .440$, $p < .001$. Simple effect analysis revealed that a distance effect was observed in all bins, min $M_{\mathrm{Diff}} = 6.55$, $ps < .01$ (see Supplementary Material Table S11 for all pairwise comparisons). On the other hand, as the bins became slower, the distance effect became more prominent (see Fig. 4). No other main effect or interactions were significant, $F\text{s} < 3.03$, $ps > .07$ (see Supplementary Material Table S9 and Table S10).

Discussion

The present study aimed to examine the distance effect, one of the most common manifestations of MNL by using the sensitivity and response bias measures of the signal detection theory. To accomplish this, we developed a go/no-go task involving a magnitude comparison based on a reference number (i.e., 5). To examine the distance effect, we categorized the numerical distance of displayed numbers as close (i.e., 3, 4, 6, and 7) and far (i.e., 1, 2, 8, and 9).

We revealed that participants' discrimination performance was superior for the far numbers, with a larger response bias for the close numbers. This evidence for a substantial distance effect on the decision variables is in line with the activation strength view (e.g., Cohen Kadosh et al., 2005; Kaufmann et al., 2005). This view, one of the most common interpretations of the distance effect in numerical cognition, suggests that activation strength of the representational location of

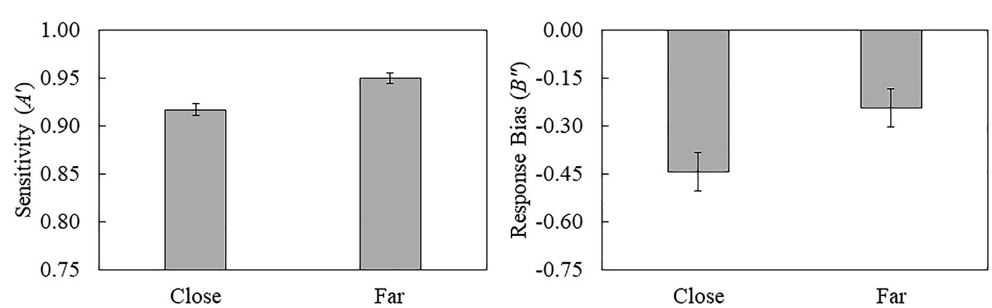

Fig. 2 Sensitivity (left panel) and response bias (right panel) measures of close and far numbers. Close numbers induced more response bias than did far numbers. Participants showed a better discrimination ability for far numbers than for close numbers. Error bars indicate 95% CI adjusted for repeated measures

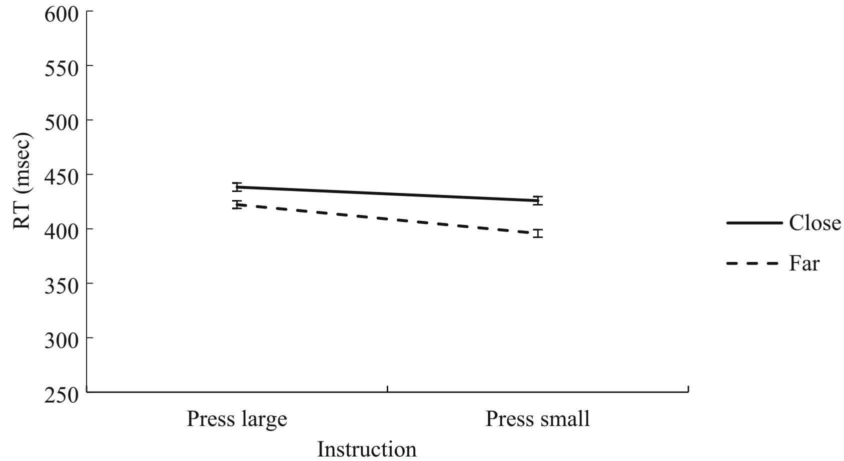

Fig 3 Distance effect as a function of instruction. Press-small condition induced a significant increase in the distance effect. Error bars indicate 95% CI adjusted for repeated measures

numbers on the MNL shows a Gaussian distribution function around the true location of each number. The distributions of any two numbers overlap more when closer (e.g., 4–5) rather than when farther apart (e.g., 1–9). While comparing magnitudes, a given number activates its own representation, as well as representations of neighboring numbers. As evidenced by previous research (Dehaene et al., 1990; Moyer & Landauer, 1967; Verguts & van Opstal, 2005), this overlap results in the need for additional time in the selection of correct responses. We predicted that the representational distribution of numbers might also induce the distance effect on sensitivity and response bias measures when comparing magnitudes. Our findings suggest that strong connections between close numbers induced by the overlapping representations not only prolong, but also interfere with, the response selection. In the current study, close numbers (3, 4, 6, and 7) might co-activate the representation of 5 according to the Gaussian distribution. Because of this co-activation, participants might have had trouble in distinguishing the signal from the noise from overlapping curves, which resulted in decreased performance in the A'. Furthermore, the larger response bias (B'') to close numbers may suggest that the activation of a particular number induces a readiness to respond to the co-activated close numbers.

When evaluating participants' performance in numerical cognition, it is common to examine number-related decisions. In particular, the diffusion model assumes that decisions are based on a noisy process in which information accumulates over time, until one of the two possible decisions are reached (for a detailed review, see Ratcliff & McKoon, 2008). The rate of accumulation of information per time unit is called the drift rate, which is similar to the sensitivity. Drift rate determines the direction of the process, which results in reaching one of two evidence barriers (criteria). The barrier represents the amount of evidence necessary before a response is initiated, and can be considered as an equivalent to the response bias. Although in the diffusion model, a model fit is executed and a prediction is made about the cumulative probability of a

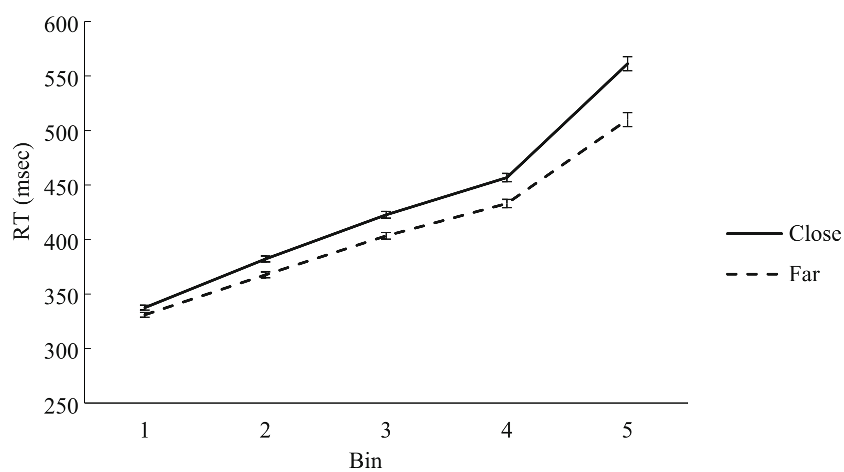

Fig. 4 Distance effect as a function of bin. As the bins become slower, a significant increase in the distance effect was observed. Error bars indicate 95% CI adjusted for repeated measures

response, theoretical interpretation of its parameters is similar to the SDT parameters. In a study that executed the diffusion model, Schwarz (2001) examined numerical comparison with a similar go/no-go task and found that the numerical distance selectively affected the drift rate. In contrast, we found that the numerical distance affected both SDT parameters. This difference, however, does not necessarily suggest a conflict between SDT and the diffusion model. As Schwarz (2001) proposed, it is possible that one factor—in our case, numerical distance—may have a complex influence and affect the parameters nonselectively. These two approaches handle data very differently (e.g., SDT parameters do not account for RT), and care is needed when making direct comparison of the findings.

One interesting finding on RT measures was that the distance effect was stronger when participants pressed small (not press large) numbers. As suggested before (Dehaene, 1997; Moyer & Landauer, 1967), the reaction time during magnitude comparison depends not only on the distance but also on the size of the numbers. The current finding provides support for this suggestion, and may imply that the distance effect observed in the RT measures may originate mainly from the faster RTs for the numbers 1 and 2 compared with 8 and 9. Furthermore, dividing RT into bins and adding them to the analysis revealed how distance effect develops with increasing processing time. Results showed that the strength of the distance effect increased as a function of the bins, meaning that the distance effect was more prominent in slower responses. This finding suggests that the spatial coding of the stimuli may remain incomplete during fast responses (see Ansorge, 2003; Mapelli et al., 2003; Sellaro et al., 2014), and therefore the representational location of numbers on the MNL are less effective on the number-based decision process. One other possible explanation of the observed strong distance effect in the slower responses could be the fine-grained information processing of close numbers based on the overlapping representations, as suggested by activation strength theory (Cohen Kadosh et al., 2005; Kaufmann et al., 2005). The bin analysis findings, however, should be interpreted cautiously. Even though numerical cognition studies often analyze the RT distribution (e.g., Gevers et al., 2006; Sellaro et al., 2014), there may be a simpler explanation for the larger effects for higher bins—namely, the skewness of RT distributions (see Wagenmakers & Brown, 2007).

The present study brings the idea of SDT approach to the understanding of number-related decisions. Specifically, SDT data suggest that number-related decisions are highly affected by the representational location of numbers on the MNL. In addition to that, RT distribution analysis implies that internal representation of numbers is less prominent during fast responses. These findings are consistent with previous literature and present further evidence for the MNL hypothesis. In order to validate the findings of the current approach, further studies may consider diversifying the go probabilities (see Schwarz, 2001), and running more trials for avoiding perfect performances or increasing the accuracy of the estimations.

The current study provides a novel idea of using the SDT measures as a practical approach to understanding number-based decision processes. We believe that using the SDT approach revealed substantial information on the number-related decisions. Finally, we suggest that studies within the context of numerical cognition should consider that number-related responses might be biased, based on our internal representation.

Data accessibility

The experiments were not preregistered. All the collected raw and processed data are publicly shared on the OSF page of the project. Statistical analyses syntax codes as well as their outputs in SPSS are also available through OSF (https://osf.io/vtzue/).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13414-021-02274-5.

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• The study was approved by the ethics committee of the Izmir University of Economics, where the study was carried out.
• The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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