Atten Percept Psychophys (2012) 74:1001–1008
DOI 10.3758/s13414-012-0302-3

Exploiting illusory effects to disclose similarities in numerical and luminance processing

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Abstract Recent studies have suggested that numerical and physical magnitudes are similarly processed by a generalized magnitude system. The present study investigates the number–luminance interaction, taking advantage of illusory effects in a cued line bisection task with numerical or nonnumerical flankers and varying levels of luminance. The results showed that both dimensions influenced bisection performance. Whereas numbers (Experiment 1) induced a systematic shift of the subjective midpoint toward the larger digit, luminance (Experiment 2) modulated the bisection performance toward the darker flanker. By combining these two illusions (Experiments 3 and 4), the two dimensions interfered with each other. This pattern of results suggests overlapping representations for physical and numerical magnitudes and highlights the value of illusory effects in cognitive research.

Keywords ATOM model · Common magnitude code · Visual illusions · Numerical magnitude · Luminance

Behavioral, neurophysiological, and neuroimaging studies have shown similarities between the representation of numbers and the representations of other physical dimensions, such as size (Cohen Kadosh et al., 2005; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Moyer & Landauer, 1967; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Szűcs & Soltész, 2007) or luminance (Cohen Kadosh et al., 2005). These similarities suggest that numerical and nonnumerical magnitudes are processed at a representational level by a generalized magnitude system consisting of a monotonic mapping system of "bigger," "brighter," "longer," and so on, which exists independently from the domain ("a theory of magnitude" [ATOM]: Bueti & Walsh, 2009; Walsh, 2003). Consequently, when processing symbolic numbers, participants may rely on an internal representation according to which symbols are converted to continuous magnitudes. Anatomically, the intraparietal sulcus has been identified as a critical brain area for amodal magnitude representation, being consistently activated during the processing of different magnitudes (Cohen Kadosh, Lammertyn, & Izard, 2008). However, it is worth noting that almost all previous studies in this context have used comparison tasks to investigate magnitude interactions, making it impossible to disentangle the shared-magnitude-representation hypothesis from an alternative hypothesis proposing that a comparison mechanism is used for distinct magnitude representations (Cohen Kadosh, Lammertyn, & Izard, 2008).

Magnitude processing is characterized by a distance effect: In comparison tasks, discrimination is facilitated when stimuli are far apart (physically or numerically) rather than close, and this effect is captured at the neural level by a modulation of parietal activation as a function of the change in distance (Cohen Kadosh et al., 2005; Kaufmann et al., 2005; Pinel, Dehaene, Rivière, & Le Bihan, 2001; Pinel et al., 2004; but see Tang, Critchley, Glaser, Dolan, & Butterworth, 2006). Evidence of shared magnitude processing arises when the distance effects of different magnitudes interact. Among the most investigated is the interaction between physical and symbolic

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size, as depicted by the numerical Stroop paradigm (Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982). In this paradigm, participants are required to indicate either the numerically or physically larger digit (relevant dimension) within a pair, while the other (irrelevant) dimension varies, yielding congruent (e.g., 2 4) or incongruent (e.g., 2 4) conditions. What are commonly observed are facilitation and interference effects, respectively, modulated by the distance in the relevant or irrelevant dimension (e.g., Tzelgov, Meyer, & Henik, 1992). Whereas evidence for the number–size interaction is quite consistent across studies, findings concerning the number–luminance interaction are less clear. In particular, by means of a modified version of the numerical Stroop task—that is, one in which numerical magnitude and the amount of luminance vary orthogonally—some studies have found number–luminance congruency effects (e.g., 2 4 or 2 4: Cohen Kadosh & Henik, 2006; Cohen Kadosh, Cohen Kadosh, & Henik, 2008), while others have not (Pinel et al., 2004). Moreover, associations between the numerically larger (vs. smaller) and darker (vs. brighter) stimuli (Cohen Kadosh & Henik, 2006), or between the numerically larger (vs. smaller) and brighter (vs. darker) stimuli (Cohen Kadosh, Cohen Kadosh, & Henik, 2008) have both been described in the literature, leading to the conclusion that relative rather than absolute luminance parameters determine the direction of the number–luminance congruency effect (Gebuis & van der Smagt, 2011).

In fact, despite similarities such as the universal distance effect, the processing of different magnitudes also differs to some extent. First, larger distances permit easier comparisons of physical magnitudes (i.e., luminance and size) than of numerical ones, and overall, physical dimensions (size and luminance) are compared faster than are symbolic ones (e.g., Cohen Kadosh et al., 2005). Second, whereas interference effects have been observed with the numerical Stroop paradigm during both numerical and physical comparisons, facilitation has often been observed only during numerical comparisons. This effect has been attributed to the fact that the processing of physical magnitude is too fast to permit number processing to accelerate size processing (e.g., Szűcs & Soltész, 2007). Additional evidence for differences in the processing of symbolic and physical magnitudes comes from neuroimaging studies that have shown overlapping activations for luminance and size processing in the occipitotemporal regions (Pinel et al., 2004), or selective activations in the left pre- and postcentral gyri for size processing (Kaufmann et al., 2005). Overall, anatomical and behavioral evidence converge to suggest the existence of shared processing mechanisms for physical and numerical magnitudes that produce distinct representations that are more perceptually mediated for physical magnitudes, and more semantically mediated for numbers.

The present study contributes to this line of research by examining the extent to which two distinct dimensions, such as number and luminance, may interact with each other even when they are irrelevant to the task and do not compete for a response. Toward this aim, we made use of a cued line bisection task with numerical or nonnumerical flankers with varying levels of luminance. The advantages of the line bisection paradigm to investigate magnitude processing are that it does not involve explicit comparison and that magnitude, represented either by Arabic numbers or by varying luminance, is irrelevant to the bisection. The cued line bisection paradigm has proved adequate for the study of cognitive processes (Fischer, 2001a). In some cases, as with *visual illusions*, bisection bias effects are primarily mediated by perceptual mechanisms. For example, in the Baldwin illusion (Baldwin, 1895), in which a line connects two different-sized squares, the shifting of the subjective midpoint toward the smaller figure is interpreted as the illusory compression of the half-line flanked by the larger figure (Fig. 1a). Similarly, the bisection of a line accompanied at each end by two different-sized bars is biased toward the shorter bar, suggesting a misestimation of the midpoint induced by the flanker disparity (Chieffi, 1996, Fig. 1b). Recently, it has been shown that semantic processing can also bias line bisection, acting as a cognitive illusion—that is, an illusion induced by higher-level mechanisms. Indeed, when different numbers were used as flankers, participants systematically misplaced the midpoint of the line toward the larger number (de Hevia, Girelli, & Vallar, 2006; de Hevia & Spelke, 2009; Fischer, 2001b; but see: Bonato et al., 2008; Gebuis & Gevers, 2011). In analogy to visual illusions, it has been proposed that the larger-digit effect reflects a *cognitive illusion*, whereby the numerical disparity is compensated for by a spatial disparity (Fig. 1c). However, whereas visual illusions may purely depend on early visual processing, cognitive illusions are the result of interactive processes between perception, cognition, and action.

Our first aim was to replicate the larger-digit effect (de Hevia et al., 2006) with a computerized version of the bisection task (Exp. 1, Fig. 2a). We then investigated the effect of luminance using rectangles of different luminosities as flankers (Exp. 2, Fig. 2a). As it is commonly known that perceptual brightness enlarges and darkness reduces (Westheimer, 2008) and that size discrepancy yields bias toward the smaller flanker (Baldwin), a darker-flanker effect (i.e., a bias toward the darker flanker) might be expected. Thus, as it has been previously suggested for other physical dimensions, we expected luminance to act at the perceptual level. Furthermore, in the two final experiments, we combined luminance and numbers by flanking lines with digits in various shades of gray, to explore the interaction between the cognitive and visual illusions (Exps. 3–4, Fig. 2a). Furthermore, across experiments, the numerical or luminance

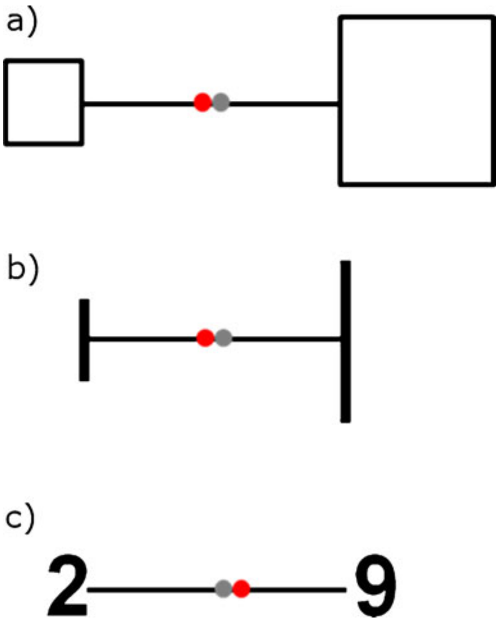

Fig. 1 (**a-c**) Examples of illusions induced in line bisection by either flanker size (**a**: Baldwin illusion, 1895; **b**: illusion reported by Chieffi, 1996) or numerical magnitude (**c**: larger-digit effect, e.g. de Hevia et al., 2006). The gray and red circles approximately indicate the positions of the real and the estimated subjective midpoints, respectively

distance between the flankers was modulated to capture variability in accessing the magnitude representations. Indeed, the presence of a distance effect would signal fine-grained processing of the target dimension versus a coarse, dichotomic discrimination of magnitudes (e.g., Henik & Tzelgov, 1982).

Method

Participants

A group of 28 right-handed students from the Department of Psychology at the University of Milano-Bicocca participated in Experiment 1 (mean age = 21.6, *SD* = 2.8; 13 males, 15 females), and a second group of 28 students participated in Experiments 2, 3, and 4 (mean age = 22.9, *SD* = 2.1; 8 males, 20 females, 2 left-handed). The order of Experiments 2, 3, and 4 was randomized across participants.

Materials, procedure, and analyses

The task was a computerized cued line bisection task. Each trial was composed of a line flanked by two numbers (Exps. 1, 3, and 4) or by two rectangles of different shades of gray (Exp. 2). To increase stimulus variability, two different line lengths (short, 236 pixels; or long, 315 pixels) were presented slightly shifted from the screen center (six different positions: up/center/down + leftward/rightward, displaced 77 pixels up or down and 102 pixels right or left from the center). The changes in line length and line position, however, did not constitute experimental manipulations, and were therefore not analyzed. Participants indicated the line midpoint by using the mouse. The mouse cursor was a vertical arrow that appeared underneath either the left or the right extreme of the line, at a fixed distance of five pixels under the stimulus, and moved only horizontally. The initial position of the mouse cursor and the position of the line on the screen were randomly assigned on each trial. The flanker pairs had different numerical distances (close, 1/2 or 8/9; or far, 1/8 or 2/9) or differences in the luminances of the gray rectangles (close, 218/198 or 81/62; far, 218/81 or 198/62, RGB coded).[1] The relative position of the larger number (Exps. 1, 3–4) or of the darker gray rectangle (Exp. 2) was counterbalanced. The numbers (Exps. 1, 3, and 4) were digits (27-point Courier New) presented at a distance of four pixels from the line, and the rectangles (Exp. 2) were approximately the same size as the digits (w × h: 16 × 22 pixels). In Experiment 1, the flankers were black digits on a white background. In Experiment 2, the flankers were gray rectangles of different shades on a mid-gray background (141 RGB, coded to be equally distant from the darkest and the brightest luminosities, used also in Exps. 3 and 4). In Experiment 3, the flankers were gray digits that increased in darkness from the smallest (218 RGB) to the largest (62 RGB) number (i.e., with a larger–darker mapping). In Experiment 4, the flankers were gray digits that increased in brightness from the smallest (62 RGB) to the largest (218 RGB) numbers (i.e., with a larger–brighter mapping). There was no time limit, although the instructions emphasized speed over accuracy. An example of the stimuli for each experiment and of the trial structure are given in Fig. 2. The session started with 10 practice trials, which were followed by 96 experimental trials, with 12 trials in each of eight conditions: Line Length (2; this factor was not analyzed) × Position Larger/Position Darker (2) × Numerical Distance (2). The stimuli were presented on a portable DELL PC (screen resolution 1,024 × 768). The participants were instructed to maintain a central position about 60 cm distant from the screen. The instructions emphasized the presence of the flankers, as well as their irrelevance for the execution of the task. Each experiment lasted approximately 10 min. Performance accuracy was calculated by subtracting the real midpoint from the subjective midpoint, so that a positive value corresponded to a rightward bias, and a negative value corresponded to a leftward bias. For each experiment, a

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[1] In order to determine the gray values, we created a linear scale of grays from 218 to 62 RGB with a mean ratio of 1.2 between adjacent grays, similarly to what was done by Tang et al. (2006) to determine different sizes.

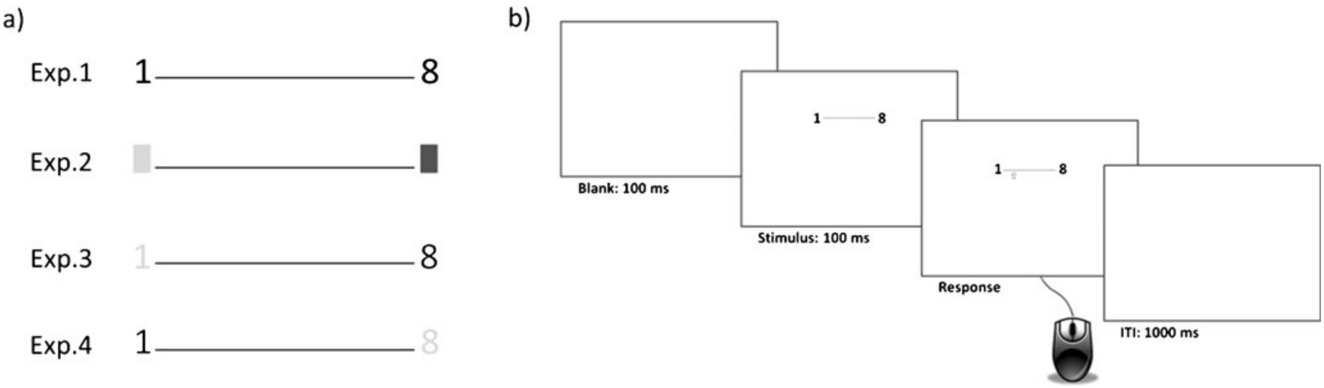

Fig. 2 (**a**) Examples of the stimuli for each experiment. (**b**) Example of a trial. After the presentation of the stimulus (line, flankers, and arrow cursor), the participant could move the arrow cursor leftward or rightward under the line by operating the mouse in his or her right peripersonal space, in order to choose the line midpoint. The response was recorded at the first mouse click

repeated measures analysis of variance (ANOVA) with Numerical Distance (close/far), and Position Larger (Exps. 1, 3, and 4: larger left/larger right) or Position Darker (Exp. 2: darker left/darker right) as within-subjects factors is reported.[2] For post-hoc comparisons, *t* tests were used.

Results

Experiment 1: Black digits flankers

The ANOVA revealed a main effect of position larger [$F(1, 27) = 133.75$, $p < .001$], indicating a bias toward the larger digit (larger right, 0.42 pixels; larger left, –1.72 pixels; Fig. 3) and no significant main effect of numerical distance ($p > .1$). Moreover, position larger interacted with numerical distance [$F(1, 27) = 15.70$, $p < .001$], indicating that the larger-digit effect was maximized when the digit flankers were far apart [larger right minus larger left: at close distance, 1.48 pixels, $t(27) = 5.28$, $p < .001$; at far distance, 2.81 pixels, $t(27) = 12.92$, $p < .001$; Fig. 4].

Experiment 2: Rectangle flankers varying in shades of gray

The effect of position darker was significant [$F(1, 27) = 4.47$, $p < .05$], indicating a bias toward the darker flanker (darker right, 0.2 pixels; darker left, –0.3 pixels; Fig. 3). No other effects or interactions were significant (ps > .1).

Since the criteria for congruency were set according to the results of this experiment, hereafter we will consider gray digit flankers with larger–darker mappings as *congruent* (Exp. 3) and gray digits flankers with larger–brighter mappings as *incongruent* (Exp. 4).

Experiment 3: Gray digits flankers with a larger–darker mapping

The main effect of position larger was significant [$F(1, 27) = 56.01$, $p < .001$], indicating a bias toward the larger number (larger right, 0.35 pixels; larger left, –2.09 pixels; Fig. 3). No significant main effect of numerical distance was found ($p = .08$). Again, position larger interacted with numerical distance [$F(1, 27) = 20.30$, $p < .001$], indicating that the larger-digit effect was maximized when flanker numbers were far apart [larger right minus larger left: at close distance, 1.35 pixels, $t(27) = 3.79$, $p < .005$; at far distance, 3.54 pixels, $t(27) = 7.84$, $p < .001$; Fig. 4].

Experiment 4: Gray digit flankers with a larger–brighter mapping

The significant main effect of position larger [$F(1, 27) = 19.40$, $p < .001$] indicated the presence of the larger-digit bias (larger right, –0.41 pixels; larger left, –1.45 pixels; Fig. 3). In contrast to Experiments 1 and 3, position larger did not interact with numerical distance ($p > .1$). No significant main effect of numerical distance was observed ($p > .1$).

Additional analyses

To understand the way in which luminance modulated the larger-digit effect, Experiments 3 and 4 were directly compared. An ANOVA with Experiment (3 or 4), Distance (close or far), and Position Larger (larger left or larger right)

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[2] Experiments 2, 3, and 4 were first analyzed with an overall ANOVA with Experiment as an additional within-subjects factor and Experiment Order as a between-subjects factor. The main effect of experiment order was not significant and did not enter in any significant interaction. Thus, we removed this factor from the following analyses. As the triple Experiment×Position Larger/Darker×Distance interaction was significant [$F(2, 21)=8.659$, $p>.005$], we analyzed and will report each experiment separately.

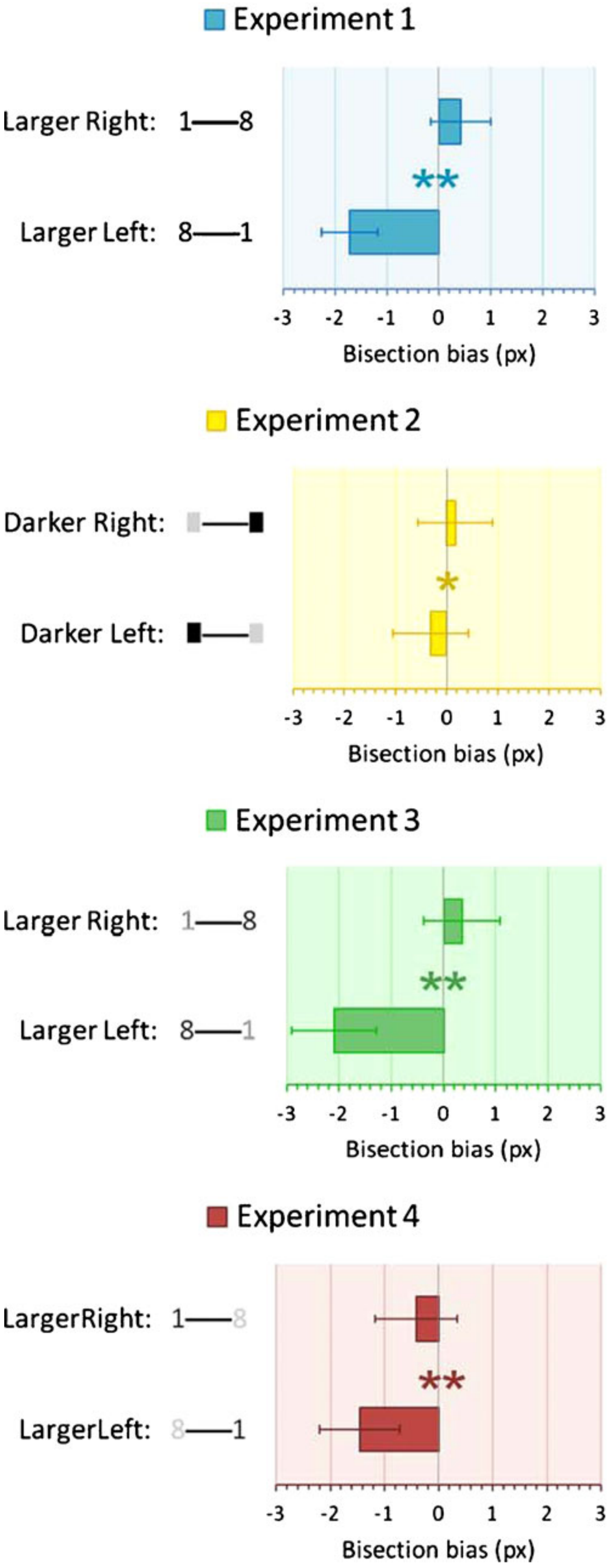

Fig. 3 Main effects (means and *SEM*s) of a flanker being larger (Exp. 1, 3, or 4) or darker (Exp. 2). Asterisks indicate the significance of the main factor (position larger/position darker) for each experiment. $^{*}p <$ .05. $^{**}p < .001$

as within-subjects factors revealed a main effect of position larger [$F(1, 27) = 64.65$, $p < .001$], as well as its interactions with experiment [$F(1, 27) = 14.16$, $p < .005$], with distance [$F(1, 27) = 6.61$, $p < .05$], and with both factors [$F(1, 27) = 12.67$, $p < .005$]. The main effect of distance was also significant [$F(1, 27) = 4.90$, $p < .05$], indicating a larger leftward bias for far (–1.10 pixels) than for close (–0.70 pixels) distances. No other main effects nor interactions were significant. The triple interaction clearly confirmed that the congruency between luminance and numbers modulated the bias toward the larger digit (Fig. 4). Indeed, whereas the larger-digit effect was modulated by the numerical distance when the visual and cognitive illusions were congruently combined (see Exp. 3 for details), when they were incongruently combined (Exp. 4), numerical information was only coarsely processed (i.e., the larger-digit effect did not interact with distance; see Exp. 4 for details). Additionally, to further substantiate the luminance effect in bisection performance, we correlated the critical effect across Experiments (2 vs. 3, 2 vs. 4). The larger-right minus larger-left difference (Exps. 1, 3, and 4), and the darker-right minus darker-left difference (Exp. 2) were taken as measures of the larger-digit or the darker-flanker effects, respectively. A positive and significant correlation between the biases in Experiments 2 and 3 ($r = .41$, $p < .05$) indicated that the participants who showed a greater numerical bias in Experiment 3 also showed a greater luminance bias in Experiment 2. Furthermore, a negative, though not significant, correlation between the biases of Experiments 2 and 4 ($r = –.29$, $p = .13$) suggested that those who showed a greater numerical bias in Experiment 4 tended to show a reduced luminance bias in Experiment 2.

Conclusions

The present study investigated the relationship between numerical magnitude and luminance by means of a cued line bisection paradigm. In Experiment 1, numerical black digits flanked the line. In Experiment 2, the line was flanked by rectangles of different luminances. In Experiments 3 and 4, numerical magnitude and luminance were combined, and numerical and luminance distance covaried in larger–darker (Exp. 3, congruent) or larger–brighter (Exp. 4, incongruent) mappings.

Experiment 1 replicated and extended previous results. In particular, the larger-digit effect was highly significant, indicating that the midpoint of the line was systematically misperceived toward the larger digit. Most importantly, the larger-digit bias interacted with the numerical distance: The effect was maximal for large numerical distances (i.e., 1–8 or 2–9) relative to small distances (i.e., 1–2 or 8–9). This finding strongly supports the cognitive-illusion hypothesis

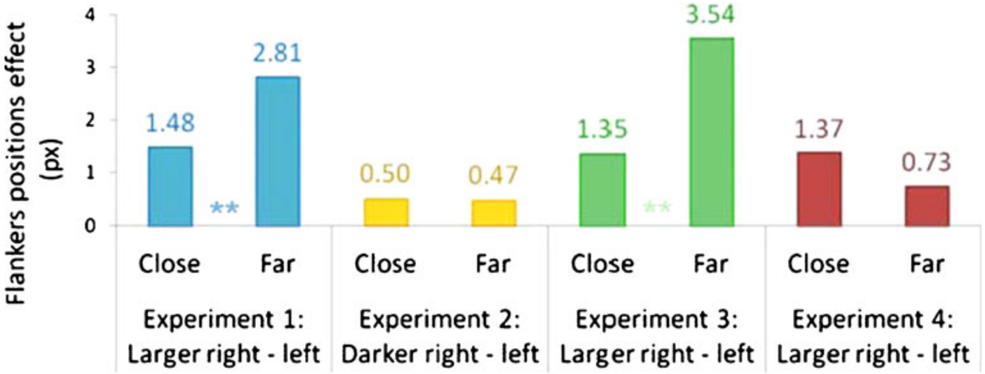

Fig. 4 Larger-digit/darker-flanker effects. The larger/darker right minus larger/darker left difference is taken as a measure of the effect of the position of the larger/darker digit. In this way, a positive value corresponded to a bisection bias toward the larger digit (larger-digit effect: Exp. 1, 3, or 4) or toward the darker flanker (darker-flanker effect: Exp. 2). Asterisks indicate within each experiment the significance of the Position Larger × Distance interaction. $^{**}p < .001$

(de Hevia et al., 2006) and indicates that numerical magnitude was processed not only automatically, but also in a refined way. The computerized bisection task used here possibly provides a more sensitive measure than does manual bisection, resulting in a distance effect that previous studies had failed to find (de Hevia et al., 2006).

Second, Experiment 2 indicated that luminance also modulates bisection performance. Indeed, as hypothesized, participants misperceived the midpoint of the line toward the darker flanker. One plausible interpretation would attribute the observed bias to the effect of luminance on size perception: In other words, a darker rectangle is perceptually perceived as smaller (Westheimer, 2008), and for this reason the direction of the bias it induces in the line bisection is analogous to those of other visual illusions (e.g., the Baldwin illusion; Baldwin, 1895). Yet, since size misperception was not explicitly tested in this study, this interpretation remains to be confirmed. Nonetheless, it is worth noticing that the numerical and luminance illusions appeared quantitatively and qualitatively different. Indeed, as compared to digits (Exp. 1), the pure effect of luminance (Exp. 2) was smaller and was not modulated by distance, which might indicate coarse processing of this dimension.

Finally, Experiments 3 and 4 replicated the larger-digit effect observed in Experiment 1 and revealed that the cognitive and visual illusions interacted, as reflected by the fact that luminance significantly modulated the bias induced by numerical information. Indeed, when the illusory effects induced by symbolic and physical magnitudes were congruently combined (Exp. 3)—that is, when larger digits were darker than smaller ones—the processing of the numerical magnitude was reflected by the larger-digit effect and by its interaction with numerical distance. On the other hand, when these illusory effects were incongruently combined (Exp. 4)—that is, when larger digits were brighter than smaller ones—the effect of numerical magnitude was reduced overall, as reflected by the size of the larger-digit effect, and by its lack of interaction with the numerical distance. The comparisons between congruent and incongruent conditions (Exp. 3 vs. 4) confirmed that, when the dimensions were incongruently combined, luminance reduced the illusory effect induced by numbers. Moreover, when numbers and luminance were incongruently combined, the access to the irrelevant numerical information was coarse, resulting in a simple dichotomic small–large discrimination. In other words, the visual illusion yielded by luminance modulated the cognitive illusion induced by symbolic magnitude, providing support for the idea of an interaction between physical and symbolic dimensions.

Overall, the present study adds to existing evidence on the interaction between physical and numerical magnitudes. In our opinion, the novelty of the paradigm supports the shared-magnitude-representation more than the shared-comparison-mechanism hypothesis, as the line bisection task does not require any explicit comparison stage between the two irrelevant dimensions. Yet, despite the fact that neither luminance nor number was relevant to the task, both dimensions influenced bisection performance: Numbers induced a systematic shift of the subjective midpoint toward the larger digit, as predicted by the cognitive-illusion hypothesis (de Hevia et al., 2006). On the other hand, luminance modulated bisection performance to reflect an illusory effect at the visual level. By combining the two illusions, the two dimensions interfered, thus suggesting the existence of distinct but overlapping representations for physical and numerical magnitudes. Moreover, being that both dimensions were irrelevant to the task, their interference could not have simply emerged by an explicit conflict at the response selection stage (Cohen Kadosh et al., 2007; Szűcs & Soltész, 2007; Tang et al., 2006). In fact, although one could argue that the line bisection might involve a comparison stage—that is, the comparison of two half-lines—this comparison represents only one of the possible strategies to identify the subjective midpoint. On the contrary, most of the paradigms used so far to study interference between the processing of different magnitudes (e.g., the numerical Stroop paradigm; Henik & Tzelgov, 1982) have explicitly required a comparison stage, putting the attended and unattended dimensions in competition within the same stimulus (e.g., the physical and numerical sizes of an Arabic number). Thus, on these grounds, although a comparison stage may not be fully excluded in bisection performance, the dimension to which it applies (i.e., the length of the line) is unrelated to the unattended but critical dimension (numerical values or luminance). For these reasons, we have opted for a shared-magnitude-representation rather than a shared-comparison-mechanism hypothesis to account for the reported results.

Finally, we acknowledge that the cued line bisection task is a complex task involving perceptual, representational, and motor components. Accordingly, it is possible that numerical and physical magnitude processing may each affect visuomotor aspects of behavior at different stages (i.e., luminance in isolation may influence the perceptual stage; luminance and number, the representational stage; number in isolation, the representational and/or motor stage) and that different brain areas subserve shared and distinct magnitude processing (Fias, Lauwereyns, & Lammertyn, 2001), with distributed overlap among magnitudes in the intraparietal sulcus. Nonetheless, specific brain regions could be involved in perceptual or motor coding, such as occipitotemporal (Pinel et al., 2004) or parietal (Walsh, 2003) areas, respectively.

In conclusion, the present study highlights the power of illusory effects in cognitive research. By deceiving our mind, illusory effects offer us a unique chance to discover how the mind works.

Author note Thanks to Mario Bonato (University of Padova, Italy) for insightful suggestions; Davide Richiello (University of Milano-Bicocca, Italy) for great help in the data collection; and Carlo Toneatto (University of Milano-Bicocca, Italy) for providing us with the computerized version of the bisection task. This work was partially supported by a MIUR Grant to L.G.

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