Numerical-spatial representation affects spatial coding: binding errors across the numerical distance effect

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Abstract Does numerical-spatial representation affect feature binding? Studies of visual attention show that poor spatial coding leads to illusory conjunctions (ICs). In numerical cognition, it has been shown that numbers and space are not totally dissociated. This association underlies the numerical distance effect (DE): faster responses as the distance between the compared digits becomes larger (2 7 vs. 2 4). We used the DE to test whether numerical-spatial representation is available to visual processes that rely on spatial coding, such as feature binding. Participants reported the larger of two colored numbers. Both numerical distance (distances 2 and 5) and number–space congruity (e.g., congruent pair, 1 3; incongruent pair, 3 1) were analyzed. Results showed a higher proportion of ICs for distance 2 than for distance 5, providing strong evidence that numerical-spatial representation (1) entails a strong location code and (2) is available to visual processes that rely on location information.

Keywords Numerical distance · Feature binding · Illusory conjunctions · Spatial coding

Different brain areas have been identified for carrying out the processing of different features, such as color, form, and motion (e.g., Livingstone & Hubel, 1988). More recently, specializations for complex stimuli including faces, scenes (Epstein, Harris, Stanley, & Kanwisher, 1999), and bodies (Downing, Jiang, Shuman, & Kanwisher, 2001) have also been identified. This distributed processing raises the question as to how different features are integrated.

The influential feature integration theory (FIT; Treisman & Gelade, 1980) describes the role of spatial attention in feature binding. According to FIT, miscombinations of visual features—*illusory conjunctions* (ICs)—appear in the absence of focal attention (Treisman & Schmidt, 1982). A number of studies have examined feature conjunctions. Features that appear close together are more likely to be conjoined than more distant features (e.g., Cohen & Ivry, 1989). With long exposures (up to 1.5 s) and low attentional load, ICs can be obtained in the periphery (Prinzmetal, Henderson, & Ivry, 1995), but not at the fovea, where spatial coding is more precise (Treisman & Schmidt, 1982). Despite several modifications over the years, FIT has maintained the important role of spatial attention as the main mechanism for the integration of independent feature codes (Quinlan, 2003).

Recently, on the basis of neuropsychology findings, a multistage model has been developed to account for dissociations between within-dimension and cross-dimension binding (Humphreys, Cinel, Wolfe, Olson, & Klempen, 2000). An example of binding within dimension is the one implying integrating vertical and horizontal segments to make either a “T” or an “L.” Cross-dimension binding is the one involving the integration of different feature dimensions, such as color and shape. The multistage account describes cross-dimension and within-dimension bindings as taking place along dorsal and ventral areas, respectively. Similar to FIT, this account still holds that binding is acquired through parietal mechanisms. That is, the parietal attention system stabilizes early conjunctions.

There are several representations of space in the primate brain (Andersen, Snyder, Bradley, & Xing, 1997). Such complex representations are known to be used by the visual system for various purposes from object identification to goal-oriented actions. In humans, numerical and spatial information have been shown to be consistently associated. For example, numerical values are represented in a horizontal vector so that small numbers are represented on the left

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side and large numbers are represented on the right side of space. This numerical–spatial association has been documented by a variety of effects, such as the SNARC (spatial numerical association response codes) effect (Dehaene, Bossini, & Giraux, 1993) and the attentional bias effect (Fischer, 2001; for a review, see Hubbard, Piazza, Pinel, & Dehaene, 2005).

The existence of such a horizontal vector was first demonstrated by the numerical distance effect reported by Moyer and Landauer (1967). In their study, participants were asked to decide which one of two simultaneously presented digits was numerically larger. Results showed a decrease in reaction time (RT) as the numerical distance between the values increased. The distance effect has been shown to affect RTs even when the numerical value is task irrelevant (Henik & Tzelgov, 1982).

The distance effect has been interpreted to reflect an analogical semantic representation of numbers. Numbers are described to be mapped across space in a way that resembles a *mental number line*. The effect of numerical distance on RTs (distance effect) reflects the distinctiveness between numbers as a function of spatial location across the mental number line. That is, two numbers that are located close together (e.g., 2 and 3) are more difficult to be differentiated than two numbers that are located far apart (e.g., 2 and 7) (see Dehaene & Changeux, 1993; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967). Even though some researchers have suggested that the distance effect may also rely on physical similarity (Cohen, 2009), the semantic component has been consistently shown in number comparison tasks (Goldfarb, Henik, Rubinsten, Bloch-David, & Gertner, 2011).

Does spatial coding, derived from long-term representation involving numbers, affect feature binding? If “close” and “distant” numbers are indeed cognitively represented in terms of location on a mental number line, we expect numbers that are close together (distance 2) to entail a less precise spatial code than numbers that are far apart (distance 5). Therefore, we expect more ICs for distance 2 than for distance 5. In other words, we should find numerical distance to affect feature binding in a similar way that retinotopic distance has been found to influence binding. Studies looking at the effect of distance on binding have consistently reported that stimuli presented in close proximity produce more binding errors than do stimuli presented farther apart (Ashby, Prinzmetal, Ivry, & Maddox, 1996; Cohen & Ivry, 1989; Prinzmetal, Ivry, Beck, & Shimizu, 2002).

We also wanted to test whether numerical spatial arrangement such as left-to-right versus right-to-left would influence binding. That is, if there is a preference for left-to-right mapping (e.g., 1–3) as opposed to right-to-left mapping (e.g., 3–1), we should find fewer ICs for the former, since spatial coding would be again more precise, therefore reducing the rate of

ICs. However, previous work has found conflicting results regarding the effects of number-line congruity on RTs (Gertner, Henik, & Cohen Kadosh, 2009; Sagiv, Simner, Collins, Butterworth, & Ward, 2006). Specifically, this factor was found to affect only a group of number–space synesthetes, but not controls. Gertner et al. interpreted this finding in terms of flexibility. Namely, nonsynesthetes' mental number line is flexible regarding direction (i.e., the mapping associating values and locations).

Method

Participants

Fifteen undergraduate volunteers (10 female; mean age, 21 years; $SD = 4.9$ years) from the psychology department of Ben-Gurion University of the Negev (BGU) received course credits for participation in the present experiment. All were naïve regarding the purpose of the experiment. All had normal or corrected-to-normal visual acuity and were not color blind. This study was carried out following the guidelines of the protocol approved by BGU's Ethics Committee.

Apparatus and stimuli

The experiment was programmed in E-Prime. Stimuli consisted of Arabic digits, which subtended $\sim 0.7^\circ \times 0.7^\circ$ of visual angle from a viewing distance of approximately 60 cm from the computer screen. Three colors were used. The parameters for luminance given by the CIE (International Commission on Luminance, 1931) are given in parentheses: orange ($x = 0.465$, $y = 0.384$, $lum = 44$ cd/m²), green ($x = 0.28$, $y = 0.31$, $lum = 43$ cd/m²), and blue ($x = 0.24$, $y = 0.296$, $lum = 38$ cd/m²).

The two colored digits were presented $\sim 2^\circ \times 2^\circ$ of visual angle to the left or to the right side of two letters. Two white letters served as fixation stimuli (H and F) and subtended $\sim 0.6^\circ \times 0.6^\circ$ of visual angle. The background was black throughout the experiment. Two hash signals served as masks. They were printed in white and were presented at $\sim 0.7^\circ \times 0.7^\circ$ of visual angle. There were four pairs of digits for each numerical distance: Distance 2 pairs consisted of 1–3, 2–4, 6–8, and 7–9, and distance 5 pairs consisted of 1–6, 2–7, 3–8, and 4–9.

Procedure

Participants were required to press the space bar when ready to start each trial. Following a variable interval (from 600 to 1,200 ms), the stimuli display was presented. The display appeared for 160 ms and consisted of the simultaneous presentation of two letters in the center of the screen and two

colored digits presented either to the left or to the right side of the letters (see Fig. 1). The letters were vertically presented, and they could be either the same (i.e., H/H, F/F) or different (i.e., H/F, F/H). Following the offset of the stimulus display, two pattern masks consisting of two hash symbols were presented for 250 ms at the location of the two digits. The presentation of the masks was followed by a fixed delay of 500 ms. Since there were always two colored numbers on every trial, two of the three possible colors were always presented. The colors were randomly selected from three possible values of orange, blue, and green. After the delay period, participants were required to give three responses. First, they were required to report whether the two letters presented in the center of the display were the “same” or “different” from each other. Second, they were required to report the *color of the largest digit*. Finally, they were required to indicate their level of confidence regarding their perception of the color of the digit by using a scale from 1 to 6 (1 = *least confident* and 6 = *most confident*).

The order of the responses was kept constant during the session. Response options were given by labeled keys on the computer keyboard. The letters *u* and *i* were labeled as “same” and “different,” respectively; the letters *j*, *k*, and *l* were labeled blue, orange, and green, respectively. The confidence response was given by pressing the numbers 1–6 (1 = *least confident*, 6 = *most confident*). The experimental trials were preceded by 30 practice trials, during which participants received feedback. There were two within-subjects factors. Number-line congruity refers to the arrangement of numbers on the horizontal axis (i.e., small numbers on the left and large numbers on the right). The presentation of the numbers were congruent (i.e., 2 4) or incongruent (i.e., 4 2) with the number-line arrangement. The distance factor refers to the numerical

distance between the two presented digits: distance 2 (e.g., 2 4) and distance 5 (e.g., 2 7).

There were three possible outcomes involving the color report: hits, ICs, and feature errors (FEs). Taking as the example the stimuli displayed in Fig. 1, a *hit* refers to the report of the color of the target—in this case, “green.” An IC refers to the report of the color of the distractor—in this case, reporting “orange.” Finally, an FE refers to the report of a color that was not presented in the display—for example, reporting “blue.”

All participants completed 288 experimental trials (72 trials for each level of the design). The experimental session took approximately 45 min to be completed, including one break in the middle of the session.

Results

Accuracy on the letter primary task was 94 %, and there was no main effect or interaction involving number-line congruity or numerical distance factors at an alpha level of .05. We computed the mean proportion of hits, ICs, and FEs for each participant for number-line congruity and numerical distance factors. Because the number-line factor had no effect on any type of response, in Fig. 2 we present only the mean proportion of hits, ICs, and FEs as a function of numerical distance.

Of main importance is the effect of number-line congruity and numerical distance on ICs. We conducted an analysis of variance (ANOVA) with number-line congruity (2) $\times$ numerical distance (2) on mean proportion of ICs as within-subjects factors. The main effect of number-line congruity and the interaction between the two factors was far from significant (both F s < 1). However, numerical distance had a dramatic impact on ICs, as revealed by the main effect of numerical distance, $F(1, 15) = 23.525$, $p = .0001$, $\eta^2 = .611$ (see Fig. 2). Participants’ reporting was consistently affected by numerical

Fig. 1 An example of the trial sequence. Following a variable interval, two letters appeared in the middle of the screen together with two colored digits presented either to the left or to the right side of the letters. At the end of the trial, participants were required to give three responses (same or different letter, the color of the digit, and confidence rating). In order to simplify the illustration, we include here only the first response screen as an example

Fig. 2 Mean proportion of responses across each one of the three response categories (hits, illusory conjunctions, and feature errors) and numerical distance

distance, as revealed by the difference in the proportion of binding errors for distance 2 (18 %) and distance 5 (10 %).¹

The occurrence of ICs reflects not just binding errors, but also feature misperceptions (FEs). That is, because we used three possible values for the report feature, blind guesses of the color of the target would produce a response classified as an IC on one third of the trials. Because random guessing would produce an equal number of FEs and ICs (as well as an equal number of correct responses), and because the FE rate is a reasonable estimate of uninformed guessing, a conservative approach would be to subtract the FE rate from the IC rate to estimate the true rate of binding errors. An estimate of the *rate of ICs* for each participant and numerical distance condition can be achieved by computing the difference between the proportion of IC rate for distance 2 (e.g., 18 %) and feature error rate for distance 2 (e.g., 1 %), producing an estimated binding error (e.g., 17 %). The use of this method for estimating binding has no effect on our main finding that the efficiency in binding is sensitive to numerical distance. An ANOVA for number-space $\times$ numerical distance on the rate of the corrected ICs (i.e., ICs minus FEs) showed only a significant effect of numerical distance, $F(1, 15) = 18.115$, $p = .001$, $\eta^2 = .574$ —significantly more ICs for distance 2 (11 %) than for distance 5 (5 %).

FEs were subjected to a separate ANOVA of number-line congruity $\times$ numerical distance. No factor affected the occurrence of such errors (all F s < 1). This result shows that the effects of numerical distance in binding are not simply due to the fact that distance 2 trials might be more difficult to solve than distance 5 trials. The difference in binding errors across numerical distance seems to arise from differences in spatial coding.

Hits and ICs as a function of confidence ratings

Here, we explored whether the level of confidence was associated with numerical distance. Previous studies

(Ashby et al., 1996; Prinzmetal et al., 2002) have shown that high levels of confidence can be associated with ICs. That is, under conditions of poor spatial coding, ICs can be experienced as real percepts. We followed Prinzmetal et al.'s (2002) approach to look at binding as a function of confidence ratings.

Here, we looked at the proportion of responses in each response category (i.e., hit, IC, FE) as a function of confidence scale. We computed the mean proportion of hits, ICs, and FEs for each participant at each level of the confidence scale (see Table 1).

We first analyzed hits across confidence bins. In order to prevent lack of statistical power, we reduced the number of confidence rating intervals to *low* (levels 1 and 2), *medium* (levels 3 and 4), and *high* (levels 5 and 6) confidence. We ran an ANOVA taking confidence ratings (3) $\times$ distance (2) on mean proportion of hits. A main effect of confidence, $F(2, 28) = 47.924$, $p = .0001$, $\eta^2 = .774$, a main effect of distance, $F(1, 14) = 13.806$, $p = .002$, $\eta^2 = .497$, and an interaction between the two factors, $F(2, 28) = 8.491$, $p = .001$, $\eta^2 = .378$, was observed. That is, when giving a correct response, participants were more confident when the distance was 5 (70 % hits) as opposed to when the distance was 2 (64 % hits). No difference was observed for *medium* confidence ratings (11 % vs. 12 % for distances 2 and 5, respectively) or for *low* confidence ratings (5 % vs. 4 % for distances 2 and 5, respectively).

We ran an ANOVA taking confidence ratings (3) $\times$ distance (2) on mean proportion of ICs. Only the interaction was statistically significant, $F(1, 14) = 17.490$, $p = .001$, $\eta^2 = .555$, reflecting that *medium* level of confidence responses were less frequent for distance 2 (3 %) than for distance 5 (7 %), $t(14) = 3.754$, $p = .002$. This pattern was reversed for the *high*-confidence responses, since observers were more confident for distance 2 (8 %) than for distance 5 (6 %), even though it did not reach significance, $t(14) = 1.811$, $p = .092$.

Discussion

When reporting the color of two simultaneously presented numbers, observers made more binding errors when the numerical distance between the numbers was 2, as compared with when the numerical distance was 5. This finding demonstrates that feature binding is sensitive to long-term representation linking numbers and space. In other words, numerical-spatial representation is available to visual processes that rely on the efficiency of spatial coding, such as feature binding. We did not find an effect of number-line congruity. This lack of effect is consistent with previous findings and stresses the flexibility of the mental number line, as suggested by Gertner et al. (2009).

¹ Cohen (2009) reported that the distance effect is sensitive to the physical similarity between the numbers. Therefore, the effect reported here might reflect differences in physical similarity between the number pairs, rather than numerical distance. Following the method proposed by Cohen, we computed the physical similarity for each pair of numbers for distance 2 and distance 5. We compared the proportion of ICs for distance 2 and 5, while controlling for physical similarity. The proportion of ICs was found to be significantly higher for distance 2 than for distance 5 when similar pairs of distance 2 (6 8 and 7 9) were compared with similar pairs of distance 5 (3 8 and 4 9), $t(14) = 2.873$, $p = .012$. The same was true when dissimilar pairs of distance 2 (1 3 and 2 4) were compared with dissimilar pairs of distance 5 (1 6 and 2 7), $t(14) = 4.401$, $p = .001$. These results show that the effect of numerical distance on ICs is not sensitive to physical similarity. We thank an anonymous reviewer for outlining this possibility.

Table 1 Mean proportions of responses as a function of numerical distance, response type, and confidence ratings, averaged over participants

		Confidence rating					
		1	2	3	4	5	6
Distance 2	Hits	.031	.020	.037	.070	.15	.48
	ICs	.025	.019	.032	.033	.0344	.044
	FEs	.0034	.0016	.0017	.0025	.0017	.0039
Distance 5	Hits	.028	.017	.046	.075	.17	.52
	ICs	.016	.013	.015	.01	.03	.03
	FEs	.007	.001	.0061	.004	.0024	.0004

Note. ICs = illusory conjunctions, FEs = feature errors

The fact that the numerical–spatial representation had no effect on the rate of feature errors (i.e., reports of features that were not presented on the display) shows that differences in binding errors across numerical distance cannot be simply attributed to overall difficulty associated with the close numerical distance. We understand the effect of distance on binding errors to reflect the quality of the spatial coding triggered by numerical–space mapping.

The possibility that long-term representation affects binding through spatial coding is in agreement with the findings reported by Ashby et al. (1996). In their study, binding is shown to be affected by the distance between target and nontarget stimuli in a way such that the larger the distance, the lower the binding error rate. Similar findings showing the effects of actual distance in bindings were also reported by Prinzmetal et al. (2002) and appear in several neuropsychology reports studying parietal (Cohen & Rafal, 1991) and subcortical (Ward, Danziger, Owen, & Rafal, 2002) functions. Importantly, in the former work, spatial coding was given by the *actual* location of the objects in the visual field, whereas here the spatial coding came from the *cognitive representation* of numbers across space.

One interesting aspect regarding the effects of long-term representation in binding refers to the observer's perceptual experience. We asked participants to rate their level of confidence regarding the perception of the reported color. We expected low confidence ratings to correspond to perceptual uncertainty. This is exactly what we found here. Observers were more likely to give uncertainty responses for distance 2 than for distance 5. As was expected, binding errors were associated to low confidence ratings, in comparison with correct reports. However, as was noted by Ashby et al. (1996; see also Prinzmetal et al., 2002), there were a great number of trials on which binding errors were associated to high confidence levels. Therefore, feature migrations associated to imprecise location coding can be as phenomenally real as correct reports. Following

the rationale proposed by Ashby et al., true binding errors are the result of poor spatial coding of feature locations. This possibility is consistent with the observation that confidence ratings associated with binding should be higher for distance 2 than for distance 5, since the former entails less precise coding. This is in accord with the findings reported here. Even though the difference in binding at high confidence did not reach statistical significance, the pattern of results observed for ICs here is consistent with the proposal of poor location coding.

The findings reported here constitute the first evidence that long-term representation—in this case, numerical–spatial association—can affect feature binding. As we mentioned previously, these findings show that spatial coding, derived from the numerical–spatial association, is available or can be used for the purposes of feature binding. Numerical–spatial mapping has been previously shown to affect motor responses (Dehaene et al., 1993; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006; Keus & Schwarz, 2005), response decisions (Daar & Pratt, 2008), and spatial attention (Fischer, 2001). Here, we show that numerical–spatial mapping affects other visual processes that do not rely on motor choices.

At the brain level, our findings are consistent with models proposing that binding is achieved by parietal functions (Humphreys et al., 2000; Treisman, 1998). Studies looking at brain activation associated with numerical processing have found parietal activity for number processing, as well as for spatial processing (Fias, Lauwereyns, & Lammertyn, 2001). One could speculate that the close link between the two dimensions (numbers and space) in parietal areas might activate, in a top-down manner, feature maps that code visual features at early states of visual processing, making binding more efficient. At this point, the neural locus for the effects of long-term representation in binding remains an open question that should be examined in future neuroimaging studies.

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