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Dimensional interaction in distance judgment

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Abstract. Participants decided under speed stress whether or not the horizontal distances between pairs of frontal locations exceeded a criterion distance. The error rate reflected parallel effects of the horizontal and vertical distance between the locations. Whereas dimensional interaction in perceptual judgment has previously been attributed either to the *perception* of the stimulus or to the response *decision* concerning the stimulus, here dimensional interaction was attributed to the process of *distance assessment* regarding the test locations. Under the proposed account, the horizontal distance between the locations could not be assessed independently of the vertical distance. Only the overall distance between the locations could be assessed. However, because the horizontal and vertical *positions* of the locations could be independently assessed, the horizontal distance between the locations was available to the extent that the vertical positions of the locations were weighted so as to minimize vertical distance prior to the assessment of overall distance. In support of this account, parallel effects of horizontal and vertical distance were not observed when participants decided whether or not pairs of locations had the same horizontal position.

Keywords: distance judgment, dimensional interaction, position

1 Introduction

Humans are prone to characterize the world in terms of quantitative attributes. Human perception therefore unfolds within a dimensional framework. The processes by which information is characterized in terms of perceptual dimensions have attracted interest because they often do not operate cleanly (Maddox & Dodd, 2003). In particular, when a stimulus varies on multiple dimensions, perceptual judgments regarding the value of the stimulus on one of the dimensions often reflect the values of the stimulus on other dimensions. This sort of imprecision has been called *dimensional interaction* (Melara, 1989, 1992). Interaction has been observed with respect to the dimensions of hue, saturation, and brightness (Burns & Shepp, 1988); pitch, loudness, and timbre (Melara & Marks, 1990a, 1990b; Taylor, 1977); color and pitch (Melara, 1989); pitch and vertical position (Melara & O'Brien, 1987); and the attack time, spectral centroid, and fine structure aspects of timbre (Caclin, Giard, Smith, & McAdams, 2007).

In the study of dimensional interaction a distinction has been drawn between *perceiving* the test stimulus and *deciding* how to respond to the stimulus. Attempts have been made to localize cases of dimensional interaction in one or the other of these components of a given task (Maddox, 1992, 2001; Maddox & Ashby, 1993, 1996; Maddox & Dodd, 2003). Recently, dimensional interaction has been observed that may not be interpretable in terms of the perception–decision dichotomy. At issue is the process whereby the distances between objects are understood in terms of an *allocentric reference frame* (Mou & McNamara, 2002; Mou, McNamara, Valiquiette, & Rump, 2004; Zhang, Mou, & McNamara, 2011). Such a frame comprises a pair of orthogonal axes, and provides a basis for encoding the locations of objects in a layout (Mou, Liu, & McNamara, 2009; Mou et al., 2004). To understand the distance between two objects in terms of an allocentric reference frame, the observer must often extract horizontal and vertical components from that distance (Mou et al., 2009).

To explore the extraction of such components, participants were tested in a *complex distance task.* On each trial of the task small circles appeared in two test locations on a computer screen. Across trials, circles appeared in a 7 column × 3 row array of locations, with adjacent locations being separated by the same physical distance on the horizontal and vertical dimension of the array. Participants were required to indicate whether the test locations were (a) less than three or (b) more than two horizontal positions apart in terms of the *location array*. Because dimensional interaction has often been observed early in the course of perceptual processing, a response signal maintained a brief interval between the presentation of the circles and the response. Thus, error rate was the crucial dependent variable (Dopkins, 2005).

The error rate in the task increased with increases in the horizontal distance between the test locations for pairs of locations that were less than three horizontal positions apart (<3 items) and decreased with increases in horizontal distance for pairs of locations that were more than two horizontal positions apart (>2 items). Of greater interest, the error rate increased with increases in *vertical* distance for <3 items and decreased with increases in vertical distance for >2 items. In short, performance reflected the *nonfocal* as well as the *focal* distance between the test locations. Of particular interest were the relative sizes of the focal and nonfocal distance effects. The data for <3 items were most important to this comparison because the horizontal and vertical distance between the test locations varied through the same three levels (0,1,2 positions), making possible a matched test of the relative sizes of the two distance effects. When the response interval was 400 ms, the error rate for <3 items depended to an equivalent degree on focal and nonfocal distance. When the response interval was 1000 ms, *differential distance effects* were observed: the error rate for <3 items depended to a greater degree on focal than on nonfocal distance. Dopkins and Sargent (2014) showed that the nonfocal distance effect occurs regardless of whether judgments are made with respect to the horizontal or the vertical dimension of physical space.

Whereas previous cases of dimensional interaction have been observed in tasks for which a single stimulus is processed per trial, the nonfocal distance effect is observed in a task for which two stimuli are processed per trial. Intuition suggests, therefore, that the underlying basis of the effect may differ from that for previous cases of dimensional interaction. The interaction in extraction (IE) hypothesis articulates this intuition. The hypothesis proposes that, because the distance between the test locations in the complex distance task is assessed on the basis of the visual angle, in terms of an implicit system of polar coordinates, which do not acknowledge the horizontal and vertical dimensions, the horizontal and vertical distance between the test locations cannot be independently assessed under the speeded conditions of the task (Foley, Ribeiro, & Da Silva, 2004). Only the overall distance between the test locations can be assessed, with the result that response decisions are based on overall distance.

The hypothesis also proposes, however, that the focal distance between the test locations is *indirectly* available through a process of dimension weighting. Dimension weighting has often been used to model situations in which the exigencies of the moment demand the focus of attention on a subset of the available perceptual dimensions (Goldstone & Steyvers, 2001; Kumada, 2001; Maddox, 1992; Muller & O'Grady, 2000). The process has sometimes been understood in Bayesian terms, with prior knowledge weighting perceptual dimensions so as to optimally evaluate sensory input (Asakura & Inui, 2011; Chen, Lu, & Holyoak, 2014). In the present case the IE hypothesis proposes that the focal distance between the test locations is indirectly available to the degree that the nonfocal positions of the test locations are weighted so as to minimize the contribution of nonfocal distance, *before* the overall distance between the locations is assessed. Such weighting is possible because the positions of the test locations are assessed in terms of rectangular coordinates, which acknowledge the horizontal and vertical dimensions. The use of rectangular coordinates may reflect local context—for example, the frame of the computer screen in the complex distance task. Alternatively, the use of these coordinates may reflect longer term contingencies. Human action is planned and carried out in terms of multiple reference frames, many of which assume rectangular coordinates (Crawford, Henriques, & Medendorp, 2011; Matin & Li, 1995; Medendorp & Van Pelt, 2011). It may be for this reason that position is understood in terms of such coordinates. Put another way, there may be a Bayesian prior for rectangular coordinates (Knill & Pouget, 2004; Knill & Richards, 1996; Maloney & Mamassian, 2009).

Differential position weighting makes the complex distance task easier to perform. Consider, for example, a complex distance task involving a 7 column × 3 row location array, in which participants are required to indicate whether the test locations are less than three or more than two horizontal positions apart (as in Dopkins, 2005). With equal position weighting, the largest distance for <3 items is 2.8 and the smallest distance for >2 items is 3. To the degree that the vertical positions are weighted so as to minimize vertical distance, the largest distance for <3 items decreases toward 2 and the required discrimination becomes easier. Such differential position weighting occurred at the 1000 ms but not at the 400 ms interval for Dopkins (2005).

Dopkins and Sargent (2014) contrasted the IE hypothesis to accounts that localize the nonfocal distance effect in the perceptual and the decisional components of the complex distance task. The interaction in perception (IP) hypothesis holds, in contrast to the IE hypothesis, that the horizontal and vertical distance between the test locations can, in principle, be independently assessed. The account holds, however, that the horizontal and vertical distance between the locations cannot, in practice, be independently assessed because the horizontal and vertical positions of a location in the complex distance task cannot be independently assessed. More concretely, the perceptual representation of the stimuli for the task is characterized by mean shift integrality (MSI), the most common conceptualization of dimensional interaction in the perceptual component of the perceptual judgment process (Kadlec & Hicks, 1998; Kingston & MacMillan, 1995; Kingston, MacMillan, Dickey, & Thorburn, 1997; MacMillan & Ornstein, 1998). As MSI increases, the perceptual representation of a set of stimuli varying along two dimensions collapses the set to an increasing degree onto a single aggregate dimension.

The interaction in decision (ID) hypothesis holds, in contrast to the IP hypothesis, that the horizontal and vertical positions of a location in the complex distance task can be independently assessed. The account holds, in contrast to the IE hypothesis, that the horizontal and vertical distance between a pair of test locations can be independently assessed. The account holds, however, that decisions in the complex distance task are based on the nonfocal as well as the focal distance between the test locations.

Dopkins and Sargent (2014) observed results supporting the IE hypothesis over the IP and ID hypotheses. They showed, first, that performance in the complex distance task was facilitated when the overall distance between the test locations was the same on the previous and the current trial. They showed, second, that differential position weighting predicted by the hypothesis for the absolute distance judgment of the complex distance task was also reflected in a concurrent relative distance judgment pitting horizontal against vertical distance.

The present study sought to further test the IE hypothesis. We focused on the claim, fundamental to the hypothesis, that distance and position are assessed in terms of different coordinate systems. As a consequence of this claim, the hypothesis predicts that distance and position information are differently accessible under speeded conditions. Whereas the horizontal or vertical distance between a pair of locations cannot be independently assessed, the horizontal or vertical positions of a pair of locations can be independently assessed. We sought to test this prediction by observing the results when the same discrimination was posed in terms of distance and position.

The stimulus material for the study was a 6 column × 6 row array of locations (see figure 1). In experiments 1 and 2 participants made speeded judgments of the horizontal distance between pairs of test locations. In experiment 1 participants decided whether the locations were less than three or more than two horizontal positions apart. In experiment 2 participants decided whether the locations were less than one or more than zero horizontal positions apart. On the basis of previous results, we expected the error rate in experiments 1 and 2 to vary with the horizontal distance between the test locations. On the basis of Weber's law, we expected the function relating error rate and horizontal distance to be steeper in experiment 1 than in experiment 2 (Burbeck & Hadden, 1993; Link, 1992). On the basis of the IE hypothesis, we expected effects of vertical distance parallel to the horizontal distance effects. This followed from the hypothesis's claim that horizontal or vertical distance cannot be independently assessed under speeded conditions. Thus, we expected the function relating error rate and vertical distance to be steeper in experiment 1 than in experiment 2. In experiment 3 participants made speeded judgments on whether the test locations shared the same or different horizontal positions. The discrimination required was the same as was required in the task of experiment 2. On the basis of previous results, we expected the error rate in experiment 3 to vary with the horizontal distance between the test locations. The IE hypothesis predicted no effect of vertical distance parallel to the horizontal distance effect. This followed from the hypothesis's claim that horizontal or vertical position can be independently assessed under speeded conditions. The experiment sought to test this prediction.

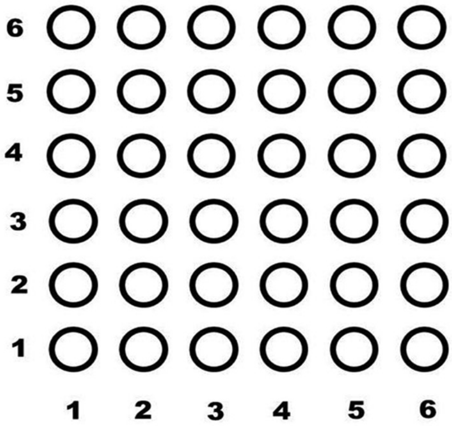

Figure 1. Location array used in all experiments of the study. Numbers are for reference in the text and were not presented to participants.

2 Experiment 1

The goal of experiment 1 was to replicate the nonfocal distance effect in the performance of distance judgments so that this distance effect could be contrasted to what happened when participants made same–different position judgments. On each trial small circles appeared in two test locations on a computer screen. Across trials, circles appeared in a 6 column × 6 row array of locations (see figure 1). Participants were required to indicate whether the test locations were less than three or more than two horizontal positions apart in terms of the location array. A response signal controlled the interval between the presentation of the circles and the response.

Notice that the array for the task was larger than the 7 column × 3 row arrays of previous studies. This change was made so that distances on the horizontal and vertical dimensions would be balanced. On the basis of the conclusions of Dopkins and Sargent (2014), we assumed that participants would base their responses on the overall distance between the test locations. Thus we expected parallel effects of horizontal and vertical distance. Specifically, we expected that the error rate would increase with increases in horizontal and vertical distance for <3 items and decrease with increases in horizontal and vertical distance for >2 items.

2.1 *Method*

2.1.1 *Participants.* The twenty participants were drawn from an undergraduate psychology course. They participated in fulfillment of a course requirement. The research was approved by the George Washington University Institutional Review Board and was performed in accordance with the World Medical Association Helsinki Declaration as revised in October 2008. Written consent was obtained from all participants prior to testing.

2.1.2 *Stimuli.* Figure 1 illustrates the location array for the experiment. Each test circle was 3 mm in diameter. Circles in horizontally and vertically adjacent locations were separated by 7 mm (from edge to edge). The participant sat approximately 60 cm from the computer screen. Each test circle therefore subtended a visual angle of approximately 0.29 deg and circles in adjacent locations were separated by a visual angle of approximately 0.66 deg. Thus, the distance between adjacent locations was relatively small.

2.1.3 *Design.* The test items for a given participant were created as follows: 180 items were created for which the horizontal distance between the test locations was 0. These items were created by combining the 30 possible ordered pairs of the six vertical positions with each of the horizontal positions of the location array. Respectively, 180, 144, 108, 72, and 36 items were created for which the horizontal distance between the test locations was 1, 2, 3, 4, and 5. To construct these items, the 5, 4, 3, 2, and 1 possible unordered pairs of horizontal position were formed for which horizontal distance was 1, 2, 3, 4, and 5, respectively. For each of these pairs of horizontal position, 36 items were constructed. The 36 items for a given pair of horizontal positions differed in the vertical positions of the test locations. Across the 36 items, the locations had the 36 different pairs of vertical positions that could be formed by sampling twice, with replacement, from the set of six vertical positions in the location array. In this way 720 items were created. Table 1 shows the numbers of items that were created for the different combinations of horizontal and vertical distance. Although the design did not equate the numbers of trials at the different combinations of horizontal and vertical distance, it had the virtue of testing all possible combinations of horizontal and vertical position for each level of horizontal distance. Of the 720 items used in the experiment, 504 were <3 items, for which the test locations were less than three horizontal positions apart, and 216 were >2 items, for which the test locations were more than two horizontal positions apart. The <3 items were made relatively prevalent for comparison with the results of Dopkins (2005) and Dopkins and Sargent (2014). The items were presented in a random order.

Table 1. Experiment 1: Numbers of trials for different combinations of horizontal and vertical distance.

Vertical distance	Horizontal distance						
	0	1	2	3	4	5	Total
0		30	24	18	12	6	90
1	60	50	40	30	20	10	210
2	48	40	32	24	16	8	168
3	36	30	24	18	12	6	126
4	24	20	16	12	8	4	84
5	12	10	8	6	4	2	42
Total	180	180	144	108	72	36	720

2.1.4 *Procedure.* The trial sequence is illustrated in figure 2. At the beginning of each trial "Ready" appeared on the computer screen. When the participant pressed the space bar of the computer, "Ready" disappeared and a pair of circles appeared. At 400 ms after the circles appeared, four asterisks appeared at the bottom of the screen. The participant was instructed (a) to push the 'B' key if the test locations were less than three horizontal positions apart and the 'N' key if the test locations were more than two horizontal positions apart, and (b) to respond concurrently with the appearance of the asterisks. If the interval between the appearance of the circles and the participant's response was less than 400 ms, the message "TOO FAST" appeared at the bottom of the screen after the participant's response and remained there until the participant pressed the space bar. If the interval was greater than 650 ms, the message "TOO SLOW" appeared in the same manner. When the participant made an error, a message appeared to that effect, after the message, if any, regarding response speed. The message remained on the screen until the participant pressed the space bar. At the beginning of the experiment and after each block of 24 trials, a message appeared asking the participant to press the space bar to see the location array. When the participant pressed the space bar, circles simultaneously appeared in the 36 test locations (see figure 1). The array of circles remained on the screen until the participant pressed the space bar.

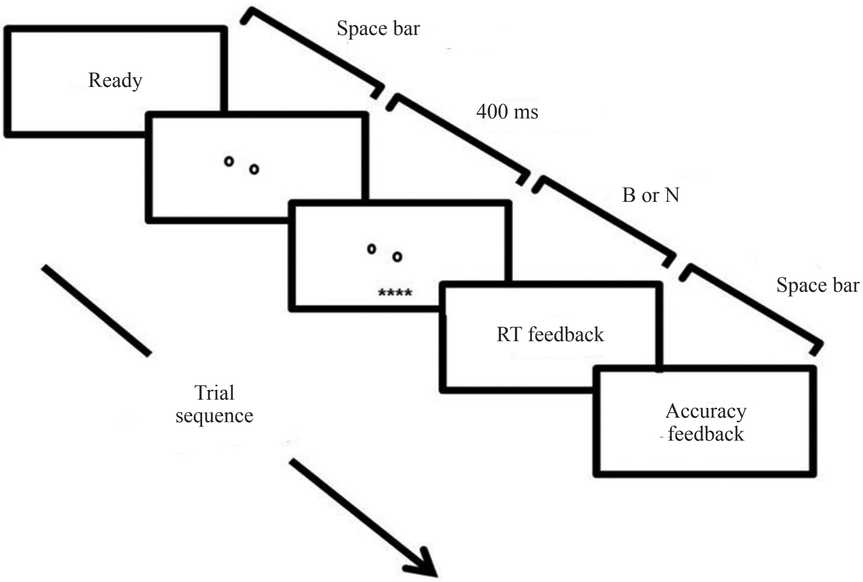

Figure 2. Experiment 1: trial sequence. Note: RT = response time.

2.2 *Results and discussion*

Figures 3 and 4 present the error-rate data for the experiment, collapsed across participants, as a function of the horizontal and vertical distance between the test locations. Generalized linear model analyses[1] showed (a) that the error rate for <3 items increased with increases in the horizontal distance between the test locations (levels 0–2 in figure 3) ($Z = 13.26$, $p < 0.0001$) and increased with increases in the vertical distance between the test locations (black line in figure 4) ($Z = 6.63$, $p < 0.0001$); and (b) that the error rate for >2 items decreased with increases in horizontal distance (levels 3–5 in figure 3) ($Z = 8.74$, $p < 0.0001$) and decreased with increases in vertical distance (gray line in figure 4) ($Z = 4.53$, $p < 0.0001$).

[1] We used a generalized linear analysis, using maximum likelihood estimation (GENMOD in SAS) because the error rates were low in some of the cells of the analysis and we did not feel that least-squares estimation (GLM in SAS) was appropriate. In all analyses we specified the identify linking function.

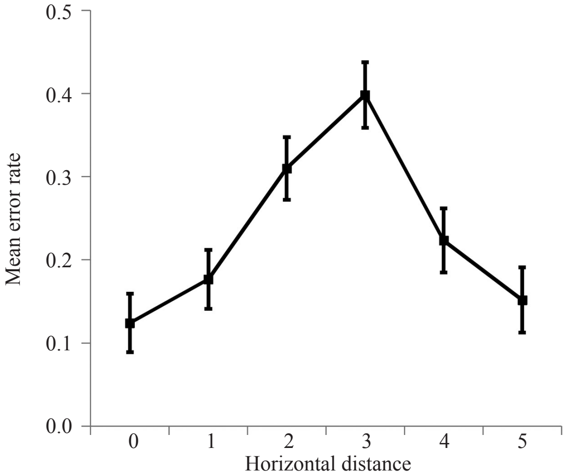

Figure 3. Experiment 1: mean error rate as a function of the horizontal distance between the test locations.

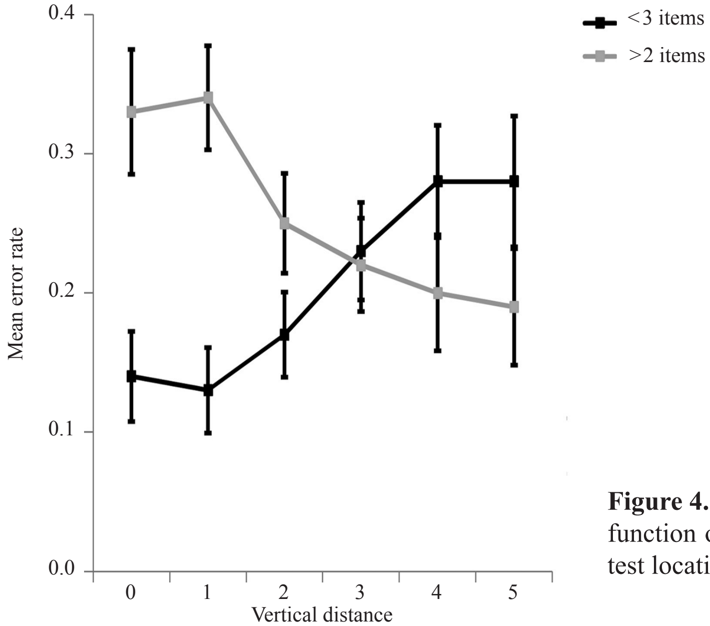

Figure 4. Experiment 1: mean error rate as a function of the vertical distance between the test locations.

The response-time data were not of primary interest, given that a response signal was used. To assess the response-time–error-rate relationship, we regressed response time against error rate in the data for the 35 different combinations of horizontal and vertical distance and the twenty participants (including dummy variables for the individual participants). Response time was positively related to error rate (coefficient = 150, $t_{680} = 9.46$, $p < 0.0001$). Response signal studies have often observed this pattern for response intervals such as were used here (Dosher, 1982, 1984).

Because no data were collected when horizontal and vertical distance were both 0, a single ANOVA could not encompass all of the response-time data for <3 items. An ANOVA limited to the data from items for which horizontal distance was greater than 0 showed that response time increased with increases in horizontal distance (levels 1–2 in figure 5) ($F_{1,19} = 5.46$, MSE = 4, 439, $p = 0.03$) and increased with increases in vertical distance (black line in figure 6) ($F_{1,19} = 5.22$, MSE = 6, 893, $p = 0.03$). Similar results were observed in an analysis limited to the data from items for which vertical distance was greater than 0. An ANOVA showed that response time for >2 items decreased with increases in horizontal distance (levels 3–5 in figure 5) ($F_{1,19} = 13.69$, MSE = 7, 874, $p = 0.002$) and decreased with increases in vertical distance (gray line in figure 6) ($F_{1,19} = 7.85$, MSE = 6, 682, $p = 0.01$).

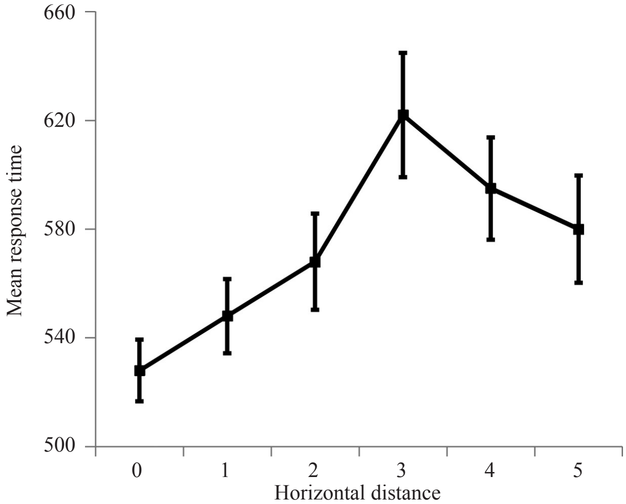

Figure 5. Experiment 1: mean response time as a function of the horizontal distance between the test locations.

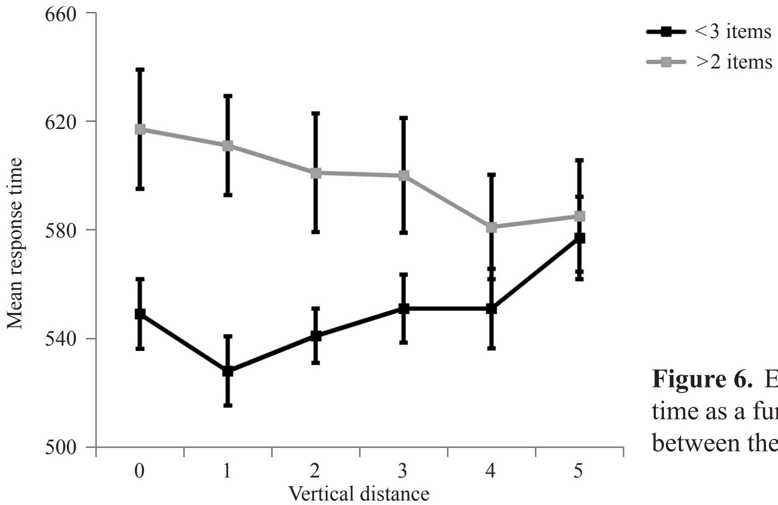

Figure 6. Experiment 1: mean response time as a function of the vertical distance between the test locations.

The general pattern of Dopkins (2005) was replicated. The error rate for <3 items increased with increases in the vertical as well as the horizontal distance between the test locations. The error rate for >2 items decreased with increases in the vertical as well as the horizontal distance between the test locations. Similar patterns were present in the response-time data. Thus, parallel effects of horizontal and vertical distance were observed.

In their more refined aspects, the results differed from the results of Dopkins (2005). Whereas Dopkins observed equivalent effects of horizontal and vertical distance at their 400 ms response interval, here the effect of horizontal distance was greater than the effect of vertical distance. We can see this in that, whereas the effect of horizontal distance in the error-rate data for <3 items involved an increase from 0.126 to 0.301 across three levels of distance (from 0 to 2), the effect of vertical distance involved an increase from 0.138 to 0.279, a smaller span, across six levels of distance (from 0 to 5). A similar pattern was present in the response-time data. Whereas the effect of horizontal distance involved an increase from 528 to 568 ms across three levels of distance (from 0 to 2), the effect of vertical distance involved an increase from 549 to 577 ms, across six levels of distance (from 0 to 5).

The IE hypothesis would attribute this pattern to differential position weighting. In more detail, according to the hypothesis, the horizontal and vertical distances between the test locations could not be independently assessed, given that the polar coordinate system for distance assessment does not acknowledge the horizontal and vertical dimensions.

However, the horizontal and vertical positions of the test locations could be independently assessed, given that the rectangular coordinate system for position assessment does acknowledge the horizontal and vertical dimensions. Thus, the vertical positions of the test locations were weighted to minimize the contribution of vertical distance before the overall distance between the test locations was assessed.

In fact, the present results increase the generality of the IE hypothesis by extending the range of conditions under which differential position weighting occurs. In past work participants have been required to indicate whether or not locations from a 7 column × 3 row array were less than 3 or more than 2 horizontal positions apart. Recall that, with equal position weighting in this task, the largest distance for <3 items is 2.8 and the smallest distance for >2 items is 3. Thus, the task can be accurately performed without differential position weighting. With this task, differential distance effects—and, by implication, differential position weighting—have been observed when the response interval has been relatively long (Dopkins, 2005) and when the distance between adjacent locations has been relatively large (Dopkins & Sargent, 2014). A case can be made that a long response interval and a large distance between adjacent locations mitigate the processing cost associated with differential position weighting. A relatively long response interval should allow dispersion of this cost. A relatively large distance between adjacent locations should make the positions of the locations more accessible and amenable to weighting. The view emerging from this past work, then, is that differential position weighting is an optional strategy used to facilitate performance of distance judgments when conditions permit.

The present results offer a more complete view of the conditions under which differential position weighting occurs. Participants were required to indicate whether or not locations from a 6 column × 6 row array were less than 3 or more than 2 horizontal positions apart. With equal position weighting in this task, the largest distance for <3 items was 5.38 and the smallest distance for >2 items was 3. Thus, the task could not be accurately performed. In other respects, the conditions of the present experiment matched those in which differential position weighting was not previously observed with a 7 column × 3 row array: the response interval was short (400 ms), and the distance between adjacent locations was relatively small. The present results show that, with a version of the task that cannot be accurately performed without differential position weighting, differential distance effects—and by implication differential position weighting—occur under the same conditions under which they do not occur with a version of the task that can be accurately performed without differential position weighting.

An important question is whether vertical distance affects the bias or the sensitivity of performance in the complex distance task. The data from experiment 1 were not stable enough to answer this question. However, we report data from a follow-up study in which each of six participants completed five sessions in the task of experiment 1. Using the aggregate data for all six participants, we plotted a psychometric function for each level of vertical distance. That is, for each level of vertical distance, we plotted the probability of a '>2' response as a function of the horizontal distance between the test locations. To plot these functions, we assumed that the probability of a '>2' response increased as an ogive function of horizontal distance. We then converted the probabilities for the different levels of horizontal distance to normal z-scores and fit linear functions to the z-scores. Linear functions fit the data well (average $R^2 = 0.98$), validating our assumption of an ogive function. We then fit psychometric functions for each level of vertical distance with the data for each of the six participants. As an index of bias, we used the value of horizontal distance for which the probability of a '>2' response was 0.50. As an index of sensitivity, we used the difference threshold—that is, the mean of the difference between the values of horizontal distance for which the probability of a '>2' response was 0.5 and 0.25 on the one hand, and 0.75 and 0.5 on the other hand (Gescheider, 1997). As figure 7 shows, the P50 index of bias decreased as a function of vertical distance ($F_{1,5} = 10.29$, MSE = 1.91, $p < 0.05$). As figure 8 shows, the difference threshold increased as a function of vertical distance ($F_{1,5} = 8.54$, MSE = 0.174, $p < 0.05$). By implication, sensitivity decreased with increases in vertical distance.

These results suggest that, in contrast to the case with many 'illusions', in which the framing context affects the bias of the required response, nonfocal distance affects the sensitivity as well as the bias of responses in the complex distance task (Morgan, 1996; Morgan, Hole, & Glennerster, 1990). The results are consistent with the IE hypothesis. Consider, first, the results for bias. Under the hypothesis, bias in the complex distance task is determined by the decision criterion, which is a value of overall distance. As the vertical distance between the test locations increases, a given value of overall distance will occur for lower and lower values of horizontal distance. Consider, second, the results for sensitivity. Under the hypothesis, the sensitivity for a given level of vertical distance depends on the differences between the values of overall distance corresponding to the various levels of horizontal distance. As vertical distance between the test locations increases, the values of overall distance corresponding to the various levels of horizontal distance will differ less.

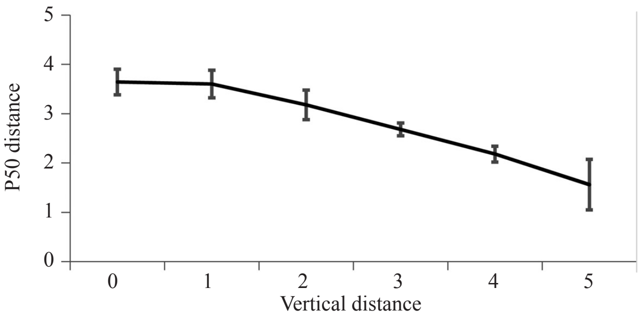

Figure 7. Experiment 1: Index of bias as a function of the vertical distance between the test locations.

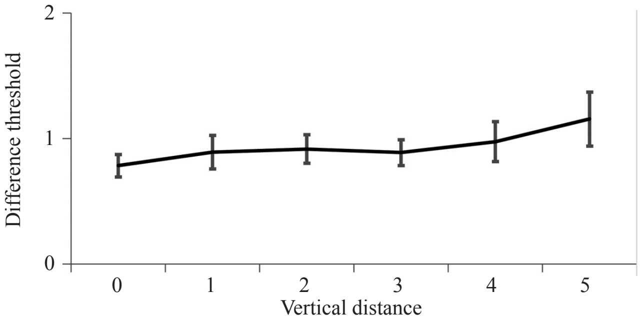

Figure 8. Experiment 1: Difference threshold as a function of the vertical distance between the test locations.

3 Experiment 2

The goal of the present study was to contrast performance in same–different judgments of horizontal position to performance in horizontal distance judgments. To do this most effectively, we reasoned that we should pit same–different judgments and distance judgments against one another with respect to the same discrimination. In experiment 2 participants performed distance judgments requiring the same discrimination as is required in same–different judgments. Participants performed a complex distance task with a 6 column × 6 row location array and a 400 ms response interval, as in experiment 1. The response criterion varied across trials. On Zero trials, which were of primary interest, participants indicated whether the test locations were less than 1 or more than 0 horizontal positions apart. Notice that the judgment required on these trials was essentially the same as for a same–different horizontal position judgment. On One trials participants indicated whether the test locations were less than two or more than one horizontal position apart. On Two trials participants indicated whether the test locations were less than three or more than two horizontal positions apart. The type of judgment required on each trial was not indicated until the test circles were presented. We reasoned as follows: participants will base their responses on One and Two trials on the overall distance between the test locations, as in experiment 1. Because participants will have no advance information regarding the type of judgment that is required on each trial, they will also base their responses on Zero trials on the overall distance between the test locations (rather than on whether the horizontal positions of the test locations are the same or different).

The object of the experiment was to observe performance on Zero trials. Our plan was to later compare this performance with performance on same–different judgments of horizontal position. On the basis of previous results, we expected the error rate to vary with horizontal distance. In addition, we expected the function relating error rate and horizontal distance to be less steep than in experiment 1. We expected this on the basis of the previous finding that the capacity for discriminating the separation between two points increases with decreases in the average separation being judged, as would be expected under Weber's law (Burbeck & Hadden, 1993; Link, 1992). The IE hypothesis predicted an effect of vertical distance parallel to the horizontal distance effect. Thus, we expected the function relating error rate and vertical distance to be less steep than in experiment 1.

3.1 *Method*

3.1.1 *Participants.* The forty participants were drawn from an undergraduate psychology course. They participated in fulfillment of a course requirement.

3.1.2 *Stimuli.* The stimuli were the same as for experiment 1 except that distances between adjacent test locations were somewhat smaller. Circles in horizontally and vertically adjacent locations were separated by a visual angle of approximately 0.40 deg.

3.1.3 *Design.* The 720 items for a given participant were generated as in experiment 1. Of these items, 50%, 16%, and 33% were randomly selected for use on Zero, One, and Two trials. The items were presented in a random order.

3.1.4 *Procedure.* The procedure was the same as for experiment 1 (see figure 2), except that a message was presented simultaneously with the test circles indicating the judgment to be performed. The message read: "Less than", either '1', '2', or '3'; or "greater than" '0', '1', or '2'.

3.2 *Results and discussion*

Figures 9–13 present the error-rate and response-time data for Zero trials, collapsed across participants, as a function of the horizontal and vertical distance between the test locations (there were too few One and Two trials to produce stable data). Generalized linear model analyses showed (a) that the error rate for <1 items neither increased nor decreased with increases in the vertical distance between the test locations (black line in figure 9) ($Z = 1.17$, $p = 0.24$), and (b) that the error rate for >0 items decreased with increases in horizontal distance (levels 1–5 in figure 10) ($Z = 8.79$, $p < 0.0001$) and decreased with increases in vertical distance (gray line in figure 9) ($Z = 4.86$, $p < 0.0001$).

To assess the response-time–error-rate relationship, we regressed response time against error rate as in experiment 1. Response time was positively related to error rate (coefficient = 154, $t_{1360} = 9.32$, $p < 0.0001$). Speed and accuracy did not trade off. ANOVAs showed (a) that response time for <1 items neither increased nor decreased with increases in vertical distance (figure 11) ($F_{1,39} = 2.40$, MSE = 17,353, $p = 0.13$), and (b) that response time for >0 items decreased with increases in horizontal distance (levels 1–5 in figure 12) ($F_{1,39} = 7.62$, MSE = 54,539, $p = 0.009$) but neither increased nor decreased with increases in vertical distance (figure 13) ($F_{1,39} < 1$).

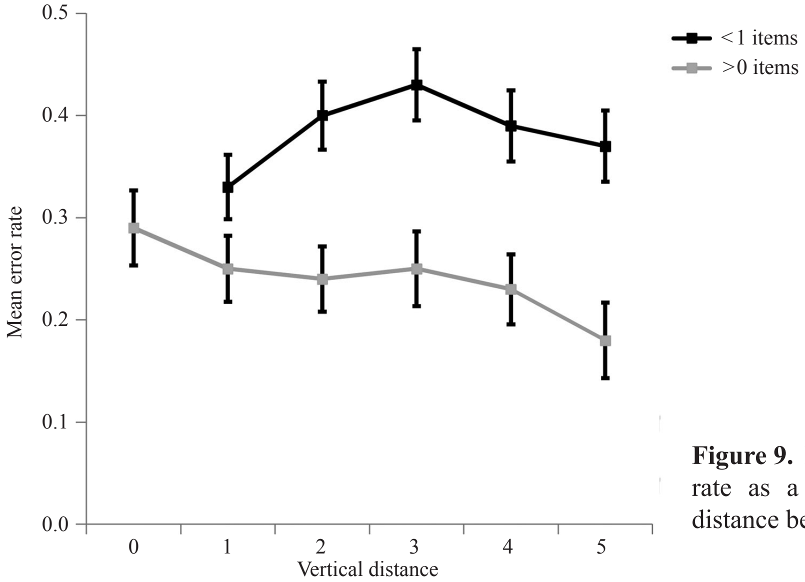

Figure 9. Experiment 2: mean error rate as a function of the vertical distance between the test locations.

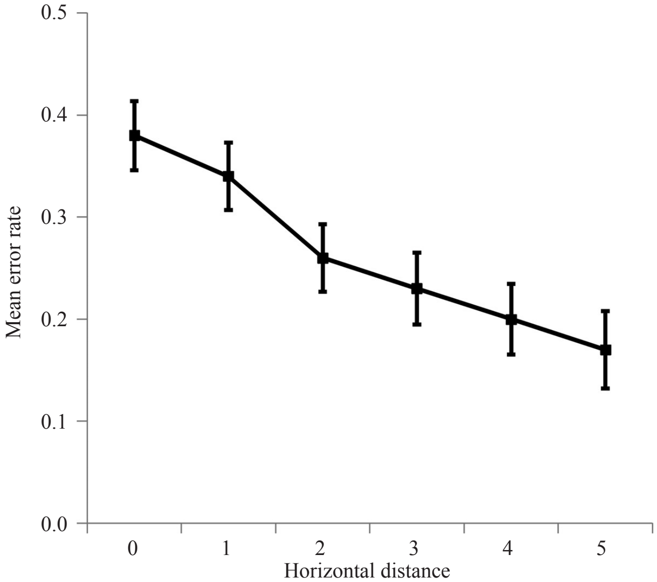

Figure 10. Experiment 2: mean error rate as a function of the horizontal distance between the test locations.

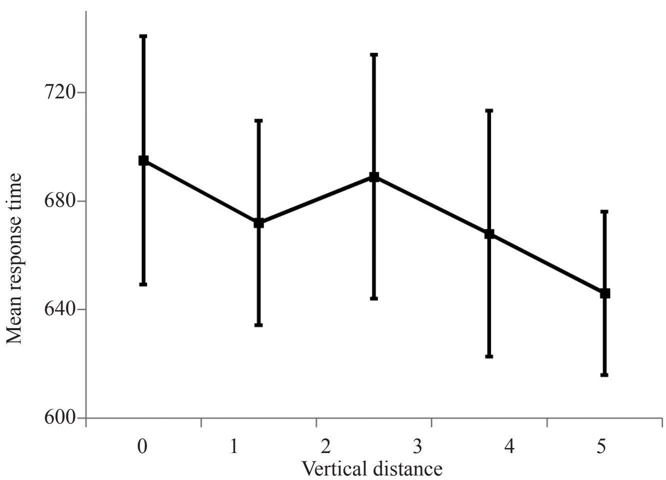

Figure 11. Experiment 2: mean response time for <1 items as a function of the vertical distance between the test locations.

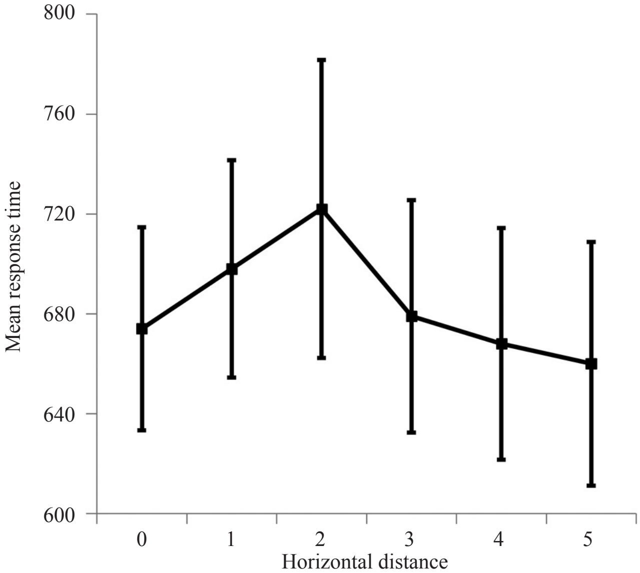

Figure 12. Experiment 2: mean response time as a function of the horizontal distance between the test locations.

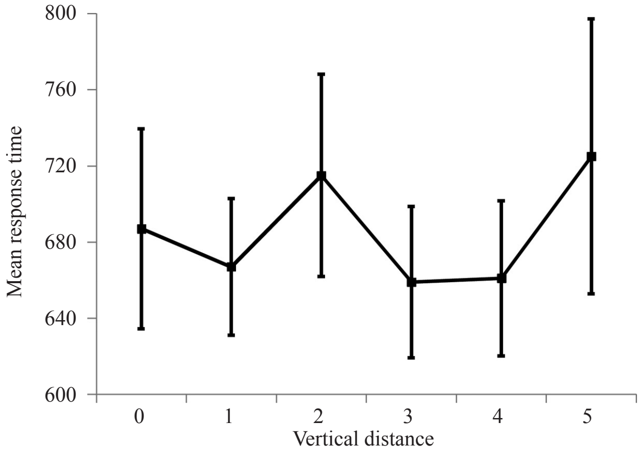

Figure 13. Experiment 2: mean response time for >0 items as a function of the vertical distance between the test locations.

To make a rough comparison of the effects of horizontal and vertical distance in experiments 1 and 2, we regressed error rate on horizontal and vertical distance for the >2 items of experiment 1 and the >0 items of experiment 2. Within experiment 1, the average regression coefficient was larger for horizontal (−0.12) than for vertical distance (−0.05) ($t_{19} = 2.69$). Within experiment 2, the average regression coefficient was larger for horizontal (−0.04) than for vertical distance (−0.01) ($t_{39} = 3.93$). The average coefficient for horizontal distance was larger in experiment 1 (−0.12) than in experiment 2 (−0.04) ($t_{58} = 7.01$). The average coefficient for vertical distance was larger in experiment 1 (−0.05) than in experiment 2 (−0.01) ($t_{58} = 2.61$).

On the Zero trials participants were required to make essentially the same discrimination as in a same–different judgment of horizontal position. The <1 and >0 items from these trials played the same role as Same and Different items in a same–different judgment. Performance neither increased nor decreased as a function of vertical distance for the <1 items. Decreasing effects of horizontal and vertical distance were observed for the >0 items. The horizontal distance function was less steep than in experiment 1, in accordance with Weber's law. The vertical distance function was also less steep than in experiment 1. Thus, the effect of vertical distance paralleled the effect of horizontal distance, in keeping with the IE hypothesis. Experiment 3 asked whether similar results would be observed for same–different judgments.

4 Experiment 3

The experiment had the following rationale: the IE hypothesis proposes that the horizontal or vertical distance between a pair of test locations cannot be independently assessed under speeded conditions. As a result, judgments of horizontal or vertical distance are based on overall distance. It follows that judgments of horizontal distance reflect the vertical as well as the horizontal distance between test locations (because both are contained in the overall distance between the locations). At the same time, the IE hypothesis proposes that the horizontal or vertical positions for a pair of test locations can be independently assessed under speeded conditions. It is on the basis of such position information that differential position weighting occurs. If the IE hypothesis is correct, and horizontal and vertical position can be independently assessed, then judgments as to whether two test locations have the same or different horizontal positions should not reflect the vertical as well as the horizontal positions of the locations. Thus, if an effect of horizontal distance occurs in performance of such judgments, a parallel effect of vertical distance should not occur. Experiment 3 tested this prediction.

On each trial of the experiment small circles appeared in two test locations on a computer screen. Across trials, circles appeared in a 6 column × 6 row array of locations, as in experiments 1 and 2. Participants were required to indicate on each trial whether the test locations had the same or different horizontal positions. The response interval was 400 ms.

The primary focus was on Different items. We expected the error rate for these items to decrease with increases in the horizontal distance between the test locations by the following rationale. We reasoned that increases in horizontal distance should make a correct 'different' response easier to emit because they should increase the evidence that the test locations were different. At the same time, however, such increases might make the same–different judgment in general more difficult to execute because they might make the test locations more difficult to bring into the same frame. On the basis of pilot work, we expected that the positive *evidence* effect would be greater than any negative *framing* effect. Thus we expected the error rate for Different items to decrease with increases in the horizontal distance between the test locations. The question of interest was whether the horizontal distance effect would be accompanied by a parallel effect of vertical distance. To answer this question, we focused in particular on Different items with vertical distances 1–5, by the following rationale. First, these were the levels of horizontal distance tested. Second, for these levels of vertical distance we could be certain that the horizontal and vertical distance effects reflected common processes. Some models of same–different judgment hold that distinct processes underlie 'same' and 'different' judgments. Whereas relatively holistic processes underlie 'same' judgments, relatively analytic processes underlie 'different' judgments (Sternberg, 1998). We reasoned that if distinct processes underlie 'same' and 'different' judgments, then whereas 'different' judgment processes would be invoked for Different items in general, 'same' judgment processes might be invoked for Different items with vertical distance 0. The impact of these 'same' judgment processes would be distributed across levels of horizontal distance but concentrated in the data point for vertical distance 0. Thus, to ensure that the horizontal and vertical distance effects reflected common processes, we reasoned that the analysis should focus on Different items with vertical distances 1–5. The question of interest was whether the error rate for these items would decrease with increases in vertical distance. The IE hypothesis predicted that the error rate would not show this pattern, for the reasons given earlier.

We were less interested in performance to Same items. We reasoned that an effect of vertical distance for Same items would be ambiguous because increases in the vertical distance might cause the error rate to increase for two reasons. First, such increases might make a correct 'same' response more difficult to emit because the same–different judgment might be based on the vertical as well as the horizontal positions of the test locations, with increases in vertical distance making the test locations more 'different'. Second, increases in vertical distance might make the same–different judgment more difficult to execute by making the test locations more difficult to bring into the same frame. Thus if the error rate for Same items increased with increases in vertical distance, this might reflect either an evidence effect or a framing effect, in the terminology introduced earlier.

4.1 *Method*

4.1.1 *Participants.* The forty participants were drawn from an undergraduate psychology course. They participated in fulfillment of a course requirement.

4.1.2 *Stimuli.* The stimuli were the same as for experiment 2.

4.1.3 *Design.* The test items for a given participant were created as in experiment 1. Of the 720 items, 180 were Same items, for which the test locations had the same horizontal position; and 540 were Different items, for which the test locations had different horizontal positions. More Different than Same items were used because Different items were the primary focus of interest in the experiment. The items were presented in a random order.

4.1.4 *Procedure.* The procedure was the same as for experiment 1 (see figure 2), except that participants were instructed to use the 'B' and 'N' keys of the computer keyboard to indicate 'same' and 'different' responses, respectively.

4.2 *Results and discussion*

Figures 14–17 present the error-rate and response-time data for the experiment, collapsed across participants, as a function of the horizontal and vertical distance between the test locations. Generalized linear analyses showed (a) that the error rate for Same items increased with increases in the vertical distance between the test locations (black line in figure 14) ($Z = 2.43$, $p = 0.01$); and (b) that the error rate for Different items decreased with increases in the horizontal distance between the test locations (levels 1–5 in figure 15) ($Z = 4.75$, $p < 0.0001$) and decreased with increases in the vertical distance between the test locations (gray line in figure 14) ($Z = 2.69$, $p = 0.007$). When the analysis for Different items was limited to levels of vertical distance greater than 0, however, the error rate decreased with increases in horizontal distance ($Z = 3.50$, $p = 0.0005$) and *increased* with increases in vertical distance ($Z = 2.78$, $p = 0.005$).

To assess the response-time–error-rate relationship, we again regressed response time against error rate as in experiment 1. Response time was positively related to error rate (coefficient = 68, $t_{1360} = 2.69$, $p < 0.05$. Speed and accuracy did not trade off. ANOVAs showed (a) that mean response time for Same items did not vary with increases in vertical distance (black line in figure 16) ($F_{1,39} < 1$) and (b) that mean response time for Different items decreased with increases in horizontal distance (levels 1–5 in figure 17) ($F_{1,39} = 14.04$, MSE = 2,764, $p < 0.0001$), and decreased with increases in vertical distance (gray line in

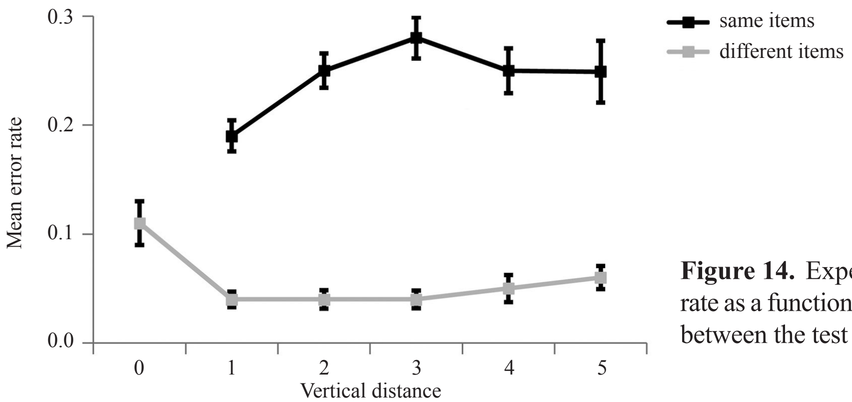

Figure 14. Experiment 3: mean error rate as a function of the vertical distance between the test locations.

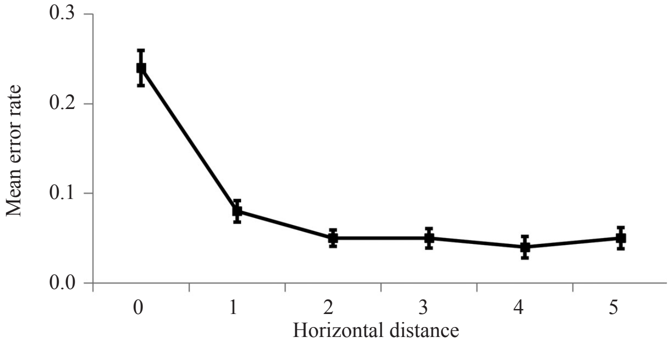

Figure 15. Experiment 3: mean error rate as a function of the horizontal distance between the test locations.

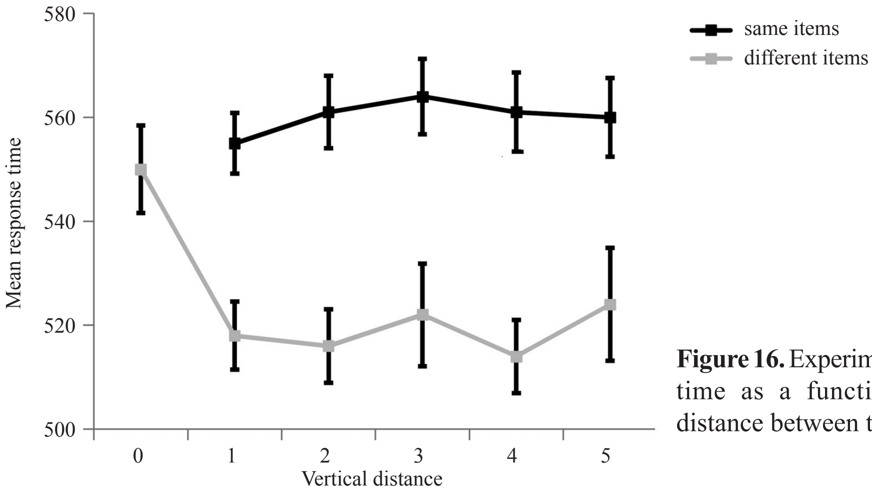

Figure 16. Experiment 3: mean response time as a function of the vertical distance between the test locations.

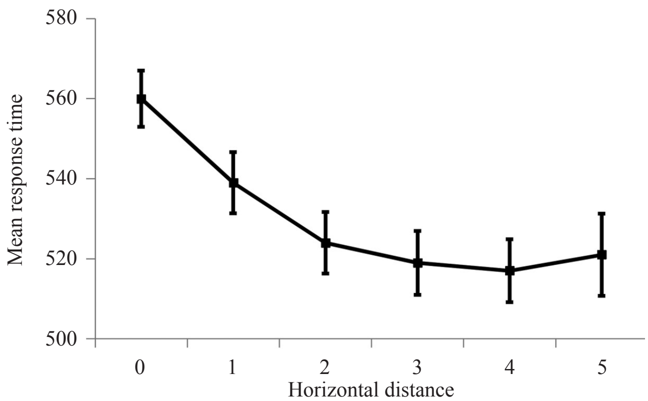

Figure 17. Experiment 3: mean response time as a function of the horizontal distance between the test locations.

figure 16) ($F_{1,39} = 18.10$, MSE = 2,747, $p < 0.0001$). When the analysis for Different items was limited to levels of vertical distance greater than 0, response time decreased with increases in horizontal distance ($F_{1,39} = 8.72$, MSE = 2,719, $p = 0.005$) but neither increased nor decreased with increases in vertical distance ($F_{1,39} < 1$).

As was expected, the error rate for Different items decreased with increases in the horizontal distance between the test locations. A similar pattern was present in the response-time data. At the same time, the error rate decreased as a function of vertical distance. A similar pattern was present in the response-time data. The decreasing pattern of vertical distance was entirely localized, however, in the contrast between the first level of vertical distance (vertical distance = 0) and the succeeding levels of vertical distance (vertical distance = 1–5).

Across vertical distances = 1–5, which were of primary interest, by the rationale given earlier, the error rate *increased* with increases in vertical distance. Response time neither increased nor decreased with vertical distance across these levels (though the means show an increasing pattern). We suggest that the decrease in error rate and response time from vertical distance = 0 to vertical distances = 1–5 reflects a categorical Stroop-like phenomenon. That is, the required 'different' response for vertical distance = 0 was impeded because the test locations shared the same vertical position (with this possibly being registered by a holistic 'same' judgment process). We suggest that the increasing pattern of error rate across vertical distances 1–5 reflects a framing effect—the test locations were increasingly difficult to bring into the same comparison frame with increases in vertical distance. Critically, across levels 1–5, the levels of primary interest, the error rate decreased as a function of horizontal distance and increased as a function of vertical distance.

As was noted, the results for Same items were of less interest. The error rate for these items increased with increases in the vertical distance between the test locations. This result may reflect the fact that judgments regarding these items were based on the vertical as well as the horizontal positions of the test locations. At the same time, this result may simply reflect a framing effect—that the test locations were increasingly difficult to bring into the same comparison frame with increases in vertical distance.

In sum, the IE hypothesis holds that horizontal distance cannot be independently assessed under speeded conditions and that horizontal distance can be independently assessed under these conditions. Thus the hypothesis predicts an effect of vertical distance parallel to the horizontal distance effect when participants make judgments of horizontal distance but not when participants make judgments of horizontal position. The present experiment tested the prediction of no parallel vertical distance effect for judgments of horizontal position. With respect to the Different items that were critical to this test, the prediction was confirmed. Across levels of vertical distance 1–5, which are the levels that were present for both horizontal and vertical distance, and the levels for which we could be assured that the horizontal and vertical distance effects reflected common processes, error rate increased with increase in vertical distance. Even if we consider the results for levels of vertical distances 0–5, the decreasing effect of vertical distance in the present experiment was much less extensive than the decreasing effect of vertical distance in experiment 2. The error rate in experiment 2 decreased across vertical distances 0–5. In contrast, the error rate in the present experiment decreased from vertical distance 0 to vertical distance 1 and increased across vertical distances 1–5. Thus, if there was some failure of independence in the assessment of horizontal position in the present experiment, the failure was of much smaller magnitude than the failure of independence in the assessment of horizontal distance in experiment 2.

5 General discussion

Dimensional interaction in perceptual judgments has previously been attributed either to the *perception* of the test stimuli or to the *decision* that is made regarding those stimuli (Maddox, 1992, 2001; Maddox & Ashby, 1993, 1996; Maddox & Dodd, 2003). In the present study we attributed dimensional interaction to the process of *distance assessment* regarding the test stimuli. According to the IE hypothesis, the focal horizontal or vertical distance between a pair of test locations cannot directly be independently assessed. Only the overall distance between the locations can be assessed. However, because the horizontal and vertical positions of a pair of locations can be independently assessed, the focal distance between a pair of locations is indirectly available to the degree that the nonfocal positions of the locations are weighted so as to minimize the contribution of nonfocal distance, before the overall distance between the locations is assessed.

Dopkins and Sargent (2014) contrasted the IE hypothesis favorably to the IP and ID hypotheses, which localize the present dimensional interaction in the perceptual and the decisional components of the complex distance task. Here we obtained further support for the IE hypothesis. We showed that parallel effects of horizontal and vertical distance occur when participants make judgments of horizontal distance but that such parallel effects do not occur when participants make judgments of same–different horizontal position. Our finding argues in particular against interpretations that localize the present dimensional interaction in the perceptual component of the complex distance task. Such interpretations would predict that an effect of nonfocal distance should always or never occur as long as the task involves perception of the same stimuli.

Although the IE hypothesis has been tested (here and in previous work) under conditions of speeded response, the same account may hold under nonspeeded conditions. In this context, it is worth noting that Dopkins and Hoyer (submitted) showed that the nonfocal distance effect occurs when the complex distance task is performed without a response signal.

As we have noted, the nonfocal distance effect is interesting in that it represents a new kind of dimensional interaction. Differential effects of focal and nonfocal distance are interesting, in addition, in that they demonstrate the role of attention in the perception of physical space. Precedent exists for the idea that the dimensions of psychological space can be weighted to reflect the requirements of the current task (Kumada, 2001; Muller & O'Grady, 2000; Nosofsky, 1986, 1987). The present results suggest that the dimensions of physical space can also be weighted in this way. These results contribute to an emerging view of physical space as subject to attentional manipulation (Liverence & Scholl, 2011; Suzuki & Cavanagh, 1997; Tsal & Shalev, 1996).

In fact, we may be able to explain differential distance effects in terms of current ideas from the study of attention. Past work has posited an *attention buffer* to explain performance in object-tracking tasks, in which participants keep simultaneous track of multiple moving objects (Intriligator & Cavanagh, 2001; Pylyshyn & Storm, 1988). To explain differential distance effects, the role of the attention buffer might be extended to distance judgments, in which participants pay simultaneous attention to two locations in assessing the distance between them. Past work suggests that attentional space is less refined than perceptual space (Intriligator & Cavanagh, 2001). To explain differential distance effects, we might consider the possibility that the refinement of attentional space varies with the circumstance. Such variation in refinement might be achieved in terms of *attentional receptive fields* (ARFs). Tsal and Shaley (1996) appealed to ARFs to account for their finding that lines are perceived as shorter when attended than when unattended. They proposed that the length of a line is estimated on the basis of the number of ARFs that the line spans and that ARFs become smaller with the focus of attention. To explain differential distance effects, we might consider the possibility that the frontal distance between two points is estimated on the basis of the number of ARFs spanned by the interpoint extent, and that ARFs are reshaped to emphasize discrimination on the focal as opposed to the nonfocal dimension.

In sum, our results speak to a new kind of dimensional interaction that occurs when participants assess the horizontal or vertical distance between pairs of locations. The results support an interpretation according to which this dimensional interaction reflects the incapacity of participants for directly assessing the horizontal or vertical distance between the locations.

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