

# Greater sensitivity in separation discrimination with closer spacing of separation levels tested

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**We explored the effects of spacing in the levels of separation tested in a separation discrimination task. Participants indicated, for pairs of test circles, whether the separation between them was greater than a standard separation. A critical set of equally-spaced separation levels was tested in two conditions. In one condition additional separation levels were interleaved between the critical levels. In the other condition additional separation levels were not interleaved. Overall, the same average level and range of levels were tested in the two conditions, and the levels tested were equally spaced in both conditions. Critically, the levels tested were more closely spaced in one condition than the other. The sensitivity of the discrimination was greater in the condition with the more as opposed to less-closely spaced levels of separation. We suggest an explanation under which separation is assessed from the number of “separation fields” between the points at which the test stimuli register and under which the separation fields are smaller or more densely distributed when the levels of separation tested are more as opposed to less-closely spaced.**

## Introduction

How do humans assess the separation between two stimuli in a frontal plane? Two views have been taken of the underlying process (Watt, 1992). According to the subtractive view the assessment reflects the difference between the positions of the stimuli in an internal localization system (Burbeck, Pizer, Morse, Ariely, Zauberman, & Rolland, 1996; Burbeck & Yap, 1990; Morgan & Regan, 1987). For example, Burbeck and Hadden (1993) proposed that separation is assessed by a system of linked position encoders. A pair of test stimuli activate multiple pairs of position encoders, with each pair of position encoders being linked by a pre-existent connection giving the separation between them. The separation between the test stimuli is derived from the relative degree of activation for pairs of

position encoders associated with different separations. According to the additive view the assessment of separation reflects the number of instances of an elementary unit distance lying between representations of the stimuli (MacEvoy & Fitzpatrick, 2006; McGraw & Whitaker, 1999; Tsal & Shalev, 1996). For example, Hisakata, Nishida, and Johnston (2016) proposed that separation is assessed in terms of neural signals that express units of local distance. The separation between two stimuli is assessed by integrating the distance units that fall between representations of the stimuli.

Short-term context effects have been interpreted as evidence regarding the process of separation assessment. For example, under the subtractive view, Burbeck and Hadden (1993) showed that the perceived separation between two test lines was increased by the presence of a flanking line if the distance between the flanking line and the nearest test line was less than the mean test-line separation. The authors proposed an account under which the area of sensitivity for the position encoders in their subtractive model (as described earlier) increased with increases in the degree of separation associated with the encoders. In support of their model Burbeck and Hadden showed that, with this added feature, the model could explain Weber’s law for separation—the finding that the sensitivity of separation discrimination decreases with increases in the level of separation from which other levels of separation are to be discriminated.

Context effects have also been taken as support for the additive view of separation assessment. A recent study explored the discrimination of separation, size, and density, contingent upon adaptation to random dot arrays (Hisakata et al., 2016). We focus here on the results for separation. A blank field and a random dot array were presented on the two sides of a screen, followed, on the respective sides of the screen, by a standard pair of dots and a test pair of dots. The task was to indicate whether the test dots were “further apart” than the standard dots. The density of the dot array was manipulated within-participants.

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Remarkably, the density of the dot array influenced *bias* in the separation discrimination task. When the density of the dot array was great enough the separation of the test dots was underestimated. That is, at the point of subjective equality—at which the test pair was perceived as matching the standard pair—the degree of test-dot separation was greater than the degree of standard-dot separation. In explanation of their results the researchers proposed that the unit distance in their additive model (as described earlier) increased with perception of a sufficiently dense dot array, with the result that fewer instances of the unit distance fell between representations of the test stimuli. More generally, the researchers interpreted their results as supporting the additive view of separation assessment. Converging results were subsequently observed with a short-term learning manipulation. After short (120 seconds) bouts of coordinated stimulation at pairs of points, the separation between pairs of test dots coincident with the stimulated points was underestimated. The results were attributed to the strengthening of lateral connections in V1 (Song, Haun, & Tononi, 2017). Such strengthening was suggested as a possible mechanism underlying the effects that Hisakata et al. (2016) observed.

By manipulating dot density Hisakata et al. (2016) obtained a bias effect that they interpreted as reflecting an increase in the unit distance by which separation is assessed and thus as supporting the additive view of separation assessment. We must consider the possibility, though, that the Hisakata et al. bias effect reflects nonperceptual processes and is thus uninformative about the perceptual process of distance assessment. One relevant nonperceptual process is decision-making; bias can be affected by decision processes, as well as by perceptual processes (Morgan, Hole, & Glennerster, 1990; Witt, Taylor, Sugovic, & Wixted, 2015). In the former case, bias can change simply as a function of how the participant sets the criterion for the response decision (Morgan, Dillenburger, Raphael, & Solomon, 2012). In some cases, this criterion setting can reflect an unconscious tendency to comply with the experimenter’s hypothesis (Morgan et al., 2012; Rosenthal & Rubin, 1978). To obtain their bias effect Hisakata et al. used an overt manipulation of dot density, of which participants were presumably well aware. We must consider the possibility, therefore, that, rather than inducing increases in the unit distance, the Hisakata et al. increases in dot density induced participants to shift their decision criteria so that a greater degree of separation was required for the test dots to be judged “further apart” than the standard dots. If this was the case the effect of the manipulation was uninformative about the perceptual process (additive vs subtractive) of distance assessment.

The present study attempted to reinforce the Hisakata et al. (2016) results using a less overt manipulation of

density. Specifically, the study attempted to reinforce the results by manipulating, between participants, the spacing of the levels of separation tested in a separation discrimination task. The rationale was as follows: Because the present level-spacing manipulation will be carried out between participants, and because this manipulation will be less overt than the Hisakata et al. (2016) dot-density manipulation, the present manipulation will be less likely than the Hisakata et al. (2016) manipulation to induce participant shifting of the decision criterion. Thus any observed results will be more confidently attributable to perceptual processes.

In more detail, participants saw a pair of test circles on each trial and indicated whether the separation between the centers of the circles was greater than a standard separation. In the less-closely spaced condition seven equally-spaced levels of separation were tested, ranging from 0.45 to 11.25 cm. In the more-closely spaced condition these seven levels were tested, as well as 18 additional interleaved levels of separation. Overall, the levels tested fell within the same range and aggregated to the same mean in both conditions. In addition, the levels tested were equally spaced in both conditions. Crucially, though, the levels tested were more closely spaced in one condition than the other. The goal was to observe the effects of these spacing differences on psychometric functions summarizing performance in the task.

In the interest of generality, two versions of the discrimination task were used. Experiment 1 used the method of single stimuli. The standard separation was not explicitly presented but was, rather, the average separation across all pairs of test circles heretofore presented in the experiment, as estimated by the participant (Morgan, 1992b; Westheimer & McKee, 1977). Experiment 2 used the more traditional method of constant stimuli (MCS) (Geschieder, 1997). Here the standard separation was explicitly presented on each trial.

## Method

### Design

Each experiment compared the same two between-participants conditions. The stimulus sets for the two conditions of each experiment were derived from a *base set* of 25 equally-spaced levels of separation. In what follows we identify the levels of separation by their index numbers within the base set (See Figure 1). In the more-closely spaced condition, the five *core* levels (levels 5, 9, 13, 17, 21) were each tested on 3/35 of the trials and the 20 other levels (the two *frame* levels [1,25] and the 18 *context* levels) were each tested on 1/35 of the trials. In the less-closely spaced condition, the five *core*

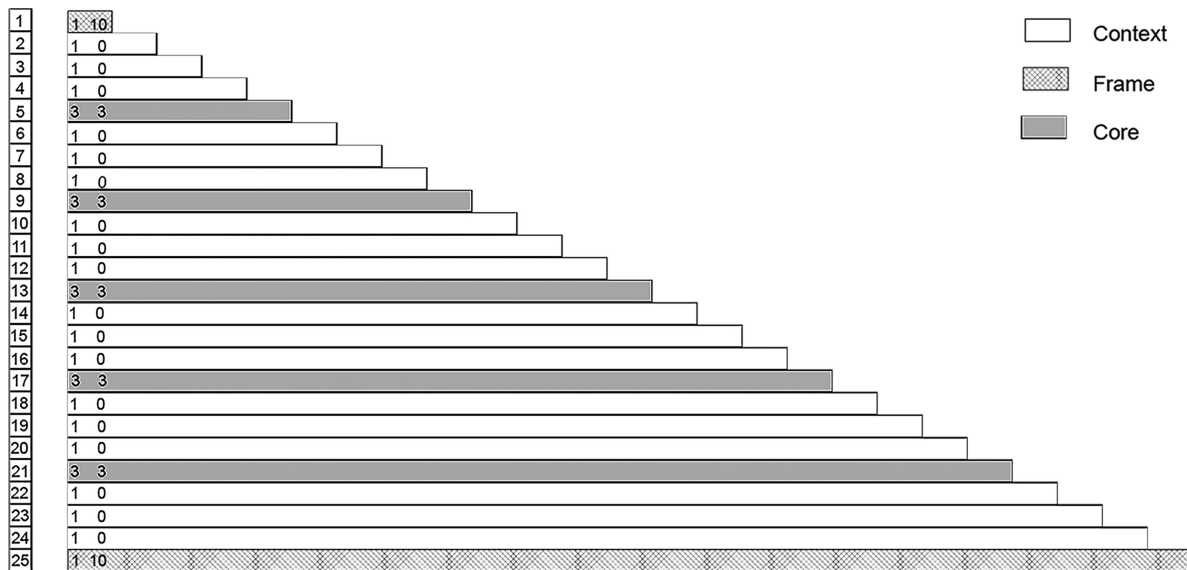


Figure 1. Design of Experiments 1 and 2. Each of the 25 *horizontal bars* corresponds to a level of separation. The numbers in the panel at the left give the index numbers of the different levels. The two numbers at the left of each bar give the proportions of times out of 35 that the corresponding level was tested in the more- and less-closely spaced conditions.

levels were each tested on 3/35 of the trials and the two frame levels were each tested on 10/35 of the trials. Thus the same seven *critical* equally-spaced separation levels (1, 5, 9, 13, 17, 21, 25) were tested in both conditions, with the five core levels (5, 9, 13, 17, 21) being tested equally frequently (each on 3/35 of the trials) in both conditions. Each participant responded on 850 trials. The level tested on each trial was determined by random sampling (a 35-element array was filled according to the proportions given earlier with codes for the levels to be tested, and an element was randomly sampled [with replacement] from the array).

## Participants

The sample size was set with a G\*Power analysis based on a preliminary study in which samples of 50 were run in the more- and less-closely spaced conditions and an effect of size ( $d$ ) 0.57 was observed for the slope difference between the conditions. Assuming an alpha level of 0.05, the analysis showed that samples of 50 in each condition would provide power of 0.81 to detect a similar effect in the present experiments (Faul, Erdfelder, Lang, & Buchner, 2007). In experiment 1, 54 participants apiece were randomly assigned to the more- and less-closely spaced conditions, with the data for four of the participants in each condition being removed (as is discussed later). In the final sample for experiment 1 the numbers of female and male participants were, respectively, 33 and 17 in the more-closely spaced and 34 and 16 in the less-closely spaced condition. The average ages in the

more-closely spaced and less-closely spaced conditions were, respectively, 20.14 and 20.32. In experiment 2, 51 and 50 participants were randomly assigned to the more- and less-closely spaced conditions, with the data for one participant in the more-closely spaced condition being removed (as is discussed later). In the final sample for experiment 2, the numbers of female and male participants were, respectively, 41 and nine in the more-closely spaced and 40 and 10 in the less-closely spaced condition. The average ages in the more-closely spaced and less-closely spaced conditions were, respectively, 19.73 and 19.82. All participants had normal or corrected-to-normal vision, participated in only one experiment, were naïve as to the purpose of that experiment, gave written consent, and were tested in accordance with the guidelines of the George Washington University Institutional Review Board.

## Procedure

Participants viewed the stimuli binocularly under standard fluorescent lighting. At the beginning of each trial, the message “Next Trial” appeared in the center of the screen. When participants pushed the space bar, the message disappeared, and two test circles appeared. Participants assessed the separation between the centers of the test circles, pushing the “B” key and “N” keys, respectively, if that separation was “less than” and “greater than” the standard separation. In Experiment 1 participants were instructed to indicate whether the separation between the test circles was greater or less than the average separation across all pairs of circles

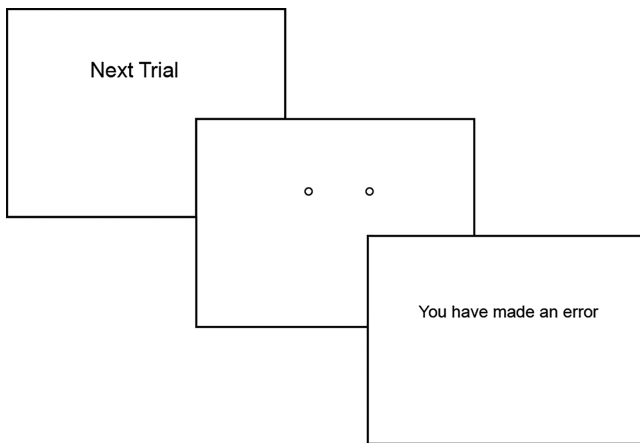


Figure 2. Trial sequence for Experiment 1.

presented in the experiment up to the current point. This is the method of single stimuli, which has been shown to produce results comparable to the more common MCS (Morgan, Watamaniuk, McKee, 2000; Westheimer & McKee, 1977). Experiment 2 used the MCS. The standard separation was presented on the screen in terms of two standard circles. For comparability with Experiment 1 this separation was the average separation for all pairs of circles in the experiment. Participants were instructed to indicate whether the separation between the test circles was greater or less than the separation between the standard circles. The test circles (Experiment 1) and the test and standard circles (Experiment 2) stayed on the screen until the participant responded. Thus participants had unlimited time to respond. Participants were encouraged to respond accurately and received feedback after making errors (See Figure 2).

## Stimuli

Each test and standard circle was 0.3 cm in diameter. In Experiment 1 the test circles were black. In Experiment 2 the test circles were green and the standard circles were blue. In both experiments the test circles were presented in the center of the screen, equidistant from the point at which the “Next Trial” message was presented. In Experiment 2 the standard circles were presented below and to the left of the test circles, with the leftmost standard circle being 4 cm to the left and 3 cm below the leftmost test circle. The separations in the base set ranged from 0.45 to 11.25 cm in equal increments. The participant sat approximately 60 cm from the computer screen. Thus each test and standard circle subtended a visual angle of approximately  $0.28^\circ$  and the separations in the base set corresponded to visual angles ranging from approximately  $0.43^\circ$  to approximately  $10.75^\circ$ . The two

test dots were shifted on each trial by amounts  $h$  and  $v$  on the horizontal and vertical axes, where  $h$  and  $v$  were drawn from a uniform distribution ranging from  $-1.6^\circ$  to  $1.6^\circ$ .

## Results

The first twenty responses in the data for each participant were dropped. With the remaining data the probability of a “greater than” response was plotted for each participant as a function of the five core separation levels (CoL) (tested equally often in the more- and less-closely spaced conditions) and as a function of all seven critical separation levels (CrL) (tested in both the more- and less-closely spaced conditions). PALAMEDES (Kingdom & Prins, 2016) was used to fit a four-parameter psychometric function, based on the cumulative normal function, to each of the two plots for a given participant. The function had parameters for  $\beta$ , the slope of the function, the reciprocal of  $\sigma$  (the standard deviation of the cumulative normal function);  $\alpha$ , or  $\mu$ : the distance value for which a “greater than” response was given with probability 0.5,  $\gamma$ , the floor parameter: the baseline probability of “greater than” response; and  $\lambda$ , the ceiling parameter: the probability of failing to indicate that the test was greater than the standard for arbitrarily large test-standard differences (Wichmann & Hill, 2001). In addition, the  $jnd$  was computed, as follows, for each participant-fitted function: The PALAMEDES inverse operation was used to find the distance values for which the participant’s fitted function gave a “greater than” response with probability 0.25 and 0.75. The  $jnd$  was then half the difference between these values.

For each of the four parameters of the psychometric function, the means and standard deviations were compared across the more- and less-closely spaced conditions. This was done for the core and the critical separation levels in each experiment. To guard against Type I errors, in light of the eight tests that were done for a given statistic (i.e., mean, standard deviation) in a given experiment, the Bonferroni method was used to set the alpha value at 0.00625.

## Experiment 1

The fit was poor for one participant in the more-closely spaced condition ( $R^2 = 0.22$  [CoL], 0.39 [CrL]) and one participant in the less-closely spaced condition ( $R^2 = 0.17$  [CoL], 0.53 [CrL]). In addition, PALAMEDES could not compute the inverses of the fitted functions for three participants in each condition. The data for these participants were removed. In the revised dataset the fit of the individual



	Slope (1/sigma)	Mu	Floor	Ceiling
Experiment 1				
Core levels				
More closely spaced	1.71 [1.25]	5.76 [0.41]	0.03 [0.03]	0.04 [0.04]
Less closely spaced	1.09 [0.90]	5.81 [0.75]	0.03 [0.03]	0.04 [0.04]
Critical levels				
More closely spaced	1.81 [1.52]	5.75 [0.38]	0.03 [0.03]	0.04 [0.04]
Less closely spaced	1.07 [1.01]	5.78 [0.76]	0.02 [0.02]	0.03 [0.03]
Experiment 2				
Core levels				
More closely spaced	2.02 [1.34]	5.99 [0.36]	0.02 [0.02]	0.03 [0.03]
Less closely spaced	1.19 [0.69]	6.15 [0.51]	0.03 [0.03]	0.03 [0.03]
Critical levels				
More closely spaced	2.19 [1.63]	5.99 [0.35]	0.01 [0.02]	0.02 [0.03]
Less closely spaced	1.17 [0.96]	6.13 [0.50]	0.02 [0.04]	0.03 [0.03]

Table 1. Experiments 1 and 2, core and critical levels of separation: Means and standard deviations of psychometric function parameters across participants. Each cell gives the mean and standard deviation (in brackets).

	Core levels	Critical levels
Experiment 1		
Slope	$t(98) = 2.83, p = 0.006^*, d = 0.57, CI_{.99} [.05-1.19]$	$t(98) = 2.88, p = 0.005^*, d = 0.58, CI_{.99} [.07-1.42]$
$\mu$	$t(98) = 0.36, p = 0.72$	$t(98) = 0.22, p = 0.83$
Floor	$t(98) = 0.40, p = 0.69$	$t(98) = 1.80, p = 0.07$
Ceiling	$t(98) = 0.36, p = 0.72$	$t(98) = 0.92, p = 0.36$
Experiment 2		
Slope	$t(98) = 3.89, p = 0.0002^*, d = 0.78, CI_{.99} [.27-1.39]$	$t(98) = 3.80, p = 0.0002^*, d = 0.76, CI_{.99} [.32-1.72]$
$\mu$	$t(98) = 1.84, p = 0.07$	$t(98) = 1.55, p = 0.12$
Floor	$t(98) = 1.90, p = 0.06$	$t(98) = 0.94, p = 0.35$
Ceiling	$t(98) = 0.90, p = 0.47$	$t(98) = 1.08, p = 0.28$

Table 2. Experiments 1 and 2, core and critical levels of separation: Differences between means for psychometric function parameters as function of level spacing. \*Statistically significant.

	Core levels	All critical levels
Experiment 1		
Slope	$F(49,49) = 1.93, p = 0.01$	$F(49,49) = 2.26, p < 0.005^*$
$\mu$	$F(49,49) = 0.30, p < 0.0001^*$	$F(49,49) = 0.25, p < 0.0001^*$
Floor	$F(49,49) = 1$	$F(49,49) = 2.25, p = 0.003^*$
Ceiling	$F(49,49) = 1$	$F(49,49) = 1.77, p = 0.046$
Experiment 2		
Slope	$F(49,49) = 3.75, p < 0.0001^*$	$F(49,49) = 2.89, p = 0.0002^*$
$\mu$	$F(49,49) = 0.50, p = 0.016$	$F(49,49) = 0.49, p = 0.013$
Floor	$F(49,49) = 0.44, p = 0.003^*$	$F(49,49) = 0.25, p < 0.0001^*$
Ceiling	$F(49,49) = 1$	$F(49,49) = 1$

Table 3. Experiments 1 and 2, Core and Critical Levels of Separation: Differences Between Standard Deviations for Psychometric Function Parameters as Function of Level Spacing \*Statistically significant.

participant functions was good, accounting, on average, for 99.7% of the variance in each condition. Across

participants the mean slope was larger in the more than in the less-closely spaced condition. In addition, the standard deviation of  $\mu$  was larger in the less than in the more-closely spaced condition. Furthermore, the standard deviation of the slope showed a trend toward being larger in the more than in the less-closely spaced condition (this result was reliable for the critical separation levels but not for the core separation levels). Inconsistent differences were observed for the standard deviations of the floor and ceiling parameters. (See Tables 1–3). Finally, the  $jnd$  in the more- and less-closely spaced conditions was, respectively, 0.62 and 0.91 cm for the core separation levels, and 0.64 and 0.94 cm for the critical separation levels. Figure 3 presents the mean probability across participants of the “greater than average” response and the best fitting psychometric functions for the critical separations as a function of Level Spacing (more-/less-closely spaced). The figure clearly shows the dependence of the

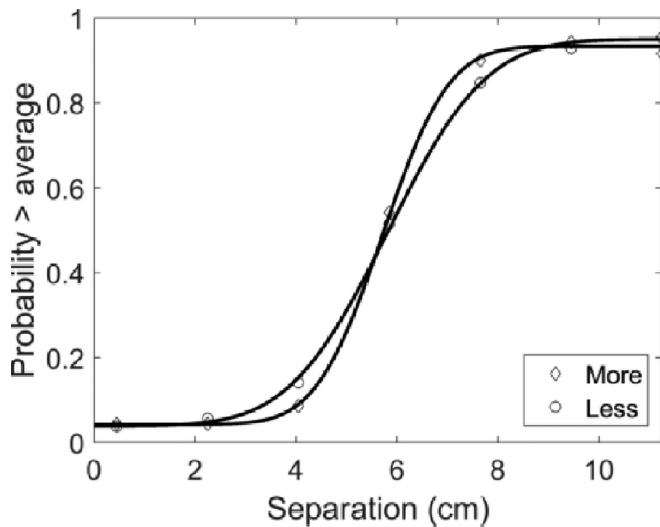


Figure 3. Experiment 1. Mean probability across participants of “greater than average” response for critical separations as a function of separation and level spacing (more-/less-closely spaced). The standard errors are as follows: more-closely spaced: 0.009, 0.009, 0.01, 0.026, 0.017, 0.011, 0.013; less-closely spaced: 0.010, 0.013, 0.018, 0.034, 0.016, 0.012, 0.009.

mean slope on Level Spacing. The dependence of the standard deviation of  $\mu$  on level spacing should also be borne in mind.

## Experiment 2

PALAMEDES could not compute the inverses of the fitted functions for one participant in the more-closely spaced condition. This participant’s data were removed. In the revised dataset the fit of the individual participant functions was good, accounting, on average, for 99.9% of the variance in the more-closely spaced and 99.8% of the variance in the less-closely spaced condition. Across participants the mean slope was larger in the more than in the less-closely spaced condition. In addition, the standard deviation of the slope was larger in the more- than in the less-closely spaced condition and the standard deviation of the floor parameter was larger in the less than in the more-closely spaced condition. Further, the standard deviation of  $\mu$  showed a trend toward being larger in the less than in the more-closely spaced condition (this result was not quite significant for either of the separation levels given the Bonferroni correction). (See [Tables 1–3](#)). Finally, the  $jnd$  in the more- and less-closely spaced conditions was, respectively, 0.50 and 0.77 cm, for the core separation levels, and 0.50 and 0.80 cm, for the critical separation levels. [Figure 4](#) presents the mean probability across participants of “greater than standard” response and the best fitting psychometric

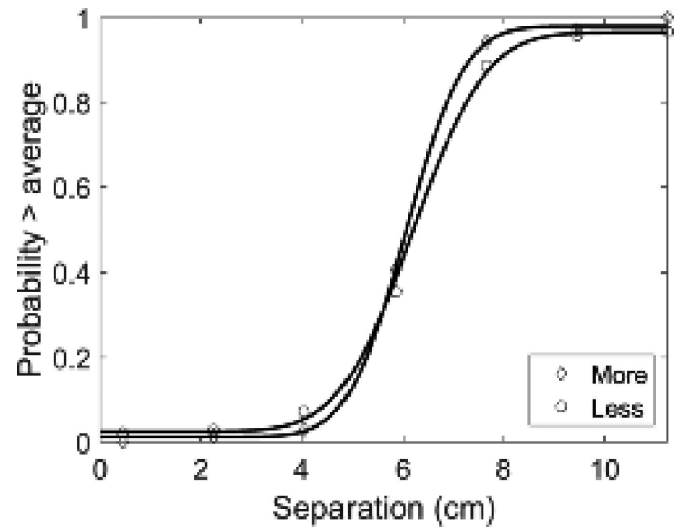


Figure 4. Experiment 2. Mean probability across participants of “greater than standard” response for critical separations as a function of separation and level spacing (more-/less-closely spaced). The standard errors are as follows: more-closely spaced: 0.003, 0.003, 0.007, 0.027, 0.008, 0.004, 0.004; less-closely spaced: 0.006, 0.006, 0.012, 0.027, 0.011, 0.006, 0.004.

functions for the critical separations as a function of level spacing (more-/less-closely spaced). The figure clearly shows the dependence of the mean slope on level spacing. Finally, it should be noted that the degree of precision in both experiments was slightly lower than has been observed with experienced participants in some previous studies ([Morgan et al., 2000](#); [Whitaker & Latham, 1997](#)). The difference in precision probably reflects the use of inexperienced, unmotivated participants.

## Discussion

In two experiments the mean slope of the cumulative normal-based psychometric function was larger for critical/core levels of separation when additional levels of separation were tested, interleaved between the critical/core levels, with the average and range of separation held constant. In addition, the standard deviation of the slope was, for some experiments and analyses, larger when additional levels of separation were tested, and the standard deviation of  $\mu$  was, for some experiments and analyses, larger when no additional levels of separation were tested. Inconsistent results were observed for the standard deviation of the floor parameter.

The most reliable of the present findings are those for mean slope. By implication the sensitivity of separation

discrimination was greater when interleaved levels of separation were tested. Thus, whereas, for Hisakata et al. (2016) the density of background dots affected bias, here the density of levels of separation affected sensitivity. We first discuss possible explanations for the present sensitivity effect and then possible explanations for the differences between our results and the results of Hisakata et al. Effects of context on the sensitivity of discrimination have only occasionally been observed in past work. The participants of Berliner and Durlach (1973) discriminated the intensities of tones in a roving-level discrimination task. A variant of  $d'$  served as the index of sensitivity, where  $d'$  is the distance between the distribution means of the to-be-discriminated stimuli on a hypothetical sensory continuum, with greater  $d$ s indicating greater sensitivity. The  $d'$  measure decreased with increases in the range of intensities tested. By implication, discrimination of intensities became less sensitive with increases in the range of intensities tested. The participants of Namdar, Ganel, & Algom (2016) discriminated the lengths of lines and the weights of water containers using the method of constant stimuli, with a standard and a test stimulus being presented on each trial and the participant indicating which was greater in length or weight. Three standards were tested in a given experimental condition, with a different set of test stimuli for each standard. Whereas the middle standard was held constant, the range of the bracketing standards was large and small in different conditions. The  $jnd$  for the middle standard was larger when the range of standards was large than when it was small. By implication, the discrimination of lengths and weights was less sensitive when the range of standards was larger.

In interpreting the present effect of context on sensitivity, we are guided by the explanations that have been offered for these previous effects. In these previous cases, a distinction has been drawn between explanations based on nonperceptual processes (e.g., memory and decision processes) and explanations based on perceptual processes (Namdar et al., 2016). On the basis of this previous work, several kinds of nonperceptual explanation might be offered for the present effect. One such explanation would appeal to the role of memory noise. Berliner and Durlach (1973) proposed that noise in the representation of their test stimuli increased with increases in the range of the stimuli, and that sensitivity decreased with increases in the noisiness of the test representations. A similar explanation could probably be given for the Namdar et al., range effect. We suggest that the present context effect may be more difficult than the aforementioned context effects to explain in terms of memory processes. In the previous cases, a lower level of sensitivity was associated with a larger range. A larger range could plausibly be understood as imposing an additional memory “load” on memory processes. In the present

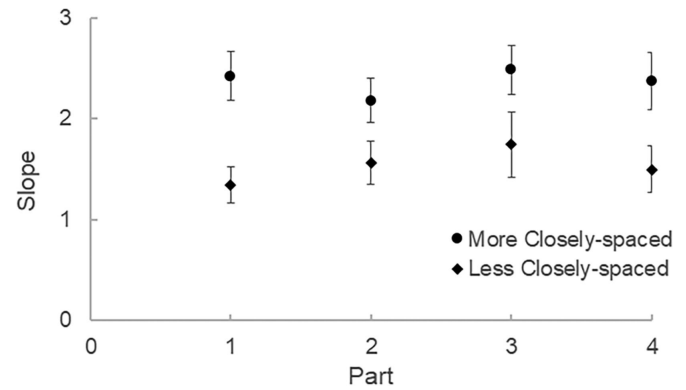


Figure 5. Experiment 1. Mean slope across participants as a function of part of session.

case, a lower level of sensitivity was associated with a smaller number of separation levels tested. Thus there was no factor that could plausibly be understood as imposing an additional memory “load.”

Another sort of nonperceptual explanation would appeal to the role of decision processes. Under this account, more-closely spaced levels of separation allowed participants to better learn the criterion value of separation that distinguished levels of separation less than and greater than the standard. Because the criterion value was better learned, sensitivity was greater. This account is plausible because learning of the proposed sort has been demonstrated in past work (Fahle & Morgan, 1996; Morgan, 1992a). The account is consistent with the greater cross-participant variability in  $\mu$  for the less- as opposed to the more-closely spaced condition (recall, though, that this difference in variability was not statistically robust). To assess the viability of this decision-based account, the cumulative normal-based psychometric function was fit to the data for the four parts of each participant’s session. The goal was to compare the slope of the function over the course of the session, under the following rationale: If the account is valid, the slope should increase – sensitivity should improve – over the course of the session because increasing amounts of learning should occur over the course of the session. In fact, for the more-closely spaced condition of Experiment 1, the slope did not vary across the session,  $F(3,147) < 1$  (See Figure 5), and, for the more-closely spaced condition of Experiment 2, the slope showed a nearly significant pattern of decrease across the session, linear component:  $F(1,49) = 7.13$ ,  $MSe = 2.66$ ,  $p = 0.01$ , overall effect:  $F(3,147) = 2.52$ ,  $MSe = 2.68$ ,  $p = 0.06$  (See Figure 6). For the less-closely spaced condition, the slope varied across the session in neither Experiment 1,  $F(3,147) < 1$ , nor Experiment 2,  $F(3,147) = 1.90$ ,  $MSe = 2.78$ ,  $p = 0.13$ . Similar results were observed in analyses that divided the session into

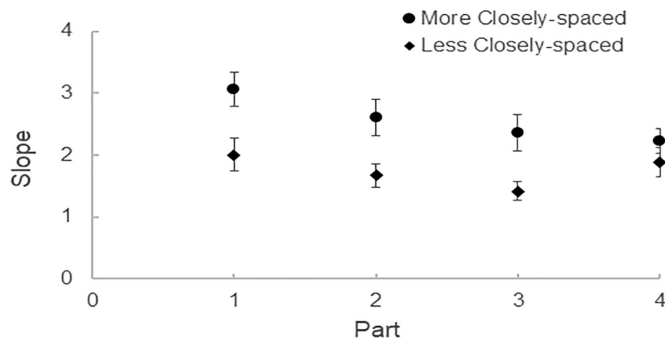


Figure 6. Experiment 2. Mean slope across participants as a function of part of session.

two and three parts. These results do not support the decision-based account.

Granting the difficulty of explaining the present sensitivity effect in terms of nonperceptual processes, can the effect be explained in terms of perceptual processes? Here past work suggests a smaller range of possible explanations. Our account builds on the account that Hisakata et al. (2016) gave for the shift in bias that they observed after adaptation to random dot arrays (see Introduction). We agree with Hisakata et al. that separation assessment involves integrating instances of a unit distance. Following these researchers, we suggest that our results may reflect changes in the unit distance that underlies the separation assessment process. We further elaborate the proposal as follows. Following views of visual and somatosensory separation assessment (Fiori & Longo, 2018; Longo & Haggard, 2011; McGraw & Whitaker, 1999; Tsal, 1999; Tsal & Shalev, 1996), we suggest that the aforementioned unit distance is instantiated in terms of receptive fields. We suggest that assessment of separation involves “counting” the number of such *separation fields* between the fields registering the test points. Because of uncertainty as to the level of the visual system at which separation is assessed, we leave many details about these separation fields (e.g., size, orientation, structure) unspecified. We suggest that separation fields decrease in size and are recruited in greater density as the tested levels of separation are more-closely spaced. With decreasing size and increasing density of separation fields discrimination becomes more sensitive because different numbers of separation fields are increasingly likely to lie between the fields that register the points corresponding to different separations. Similar proposals regarding “counting” of subunits have been made in the realm of separation, length, and numerosity assessment (Fiori & Longo, 2018; Longo & Haggard, 2011; McGraw & Whitaker, 1999; Solomon & Morgan, 2018; Tsal, 1999; Tsal & Shalev, 1996). Similar proposals regarding recruitment have been made to account for the effects of attentional

focus in the perception of position (Suzuki & Cavanagh, 1997). Similar proposals linking density of separation fields and discrimination have been made in the realm of somatosensory perception (Longo & Haggard, 2011). The proposed account is more consistent than is the above-described decision-based account with the lack of within-session improvement that we observed in our slope data. Recent work on attention suggests that receptive fields can be re-configured rather quickly (Anton-Erxleben & Carrasco, 2013; Treue & Martinez-Trujillo, 2014). Thus the proposed account would not predict improvement over the course of the session. The proposed account could accommodate the greater variability that Experiment 1 demonstrated in  $\mu$  for the Less as opposed to the more-closely spaced condition. If separation assessment involves “counting” separation fields, then a particular criterion number of separation fields must be associated with a particular standard degree of separation. With decreasing size or increasing density of separation fields, the criterion number for a given participant should more closely match the objective standard. Criterion variability across participants should decrease. Finally, the proposed account could accommodate the greater variability that experiments 1 and 2 demonstrated in slope for the more-closely spaced as opposed to the less-closely spaced condition. This difference in variability could be attributed to variability in the processes underlying receptive-field alteration.

Like the account that Hisakata et al. (2016) offered for their results, the account that we have offered assumes the additive assessment of separation. Granting the truth of the account, our results complement the support that Hisakata et al. and Song et al. (2017) have provided for the additive view of separation assessment. Of course, the present results do not definitively support the account that we have offered. In fact, the results do not demand explanation in terms of perceptual processes. Alternatively, nonperceptual processes or a combination of perceptual and nonperceptual processes may be responsible. Research is currently under way to sort the matter out more completely.

Although we observed an effect of level spacing on the mean slope of participant psychometric functions, we observed no such effect on the mean  $\mu$ . Thus, we observed an effect on the sensitivity but not the bias of separation discrimination. In contrast, Hisakata et al. (2016) observed effects of context on the bias but not on the sensitivity of separation discrimination. To account for the difference between our results and those of Hisakata et al. (2016), we focus on the decision component of separation discrimination. If the size and density of separation fields can vary with context, as our results suggest, then the criterion number of separation fields must also vary with context. We have suggested that separation fields became smaller and more dense with closer spacing of separation levels



in our experiments, with the result that sensitivity increased. We suggest that, as part of the perceptual process by which separation fields became smaller and more dense, the criterion number of separation fields was set in synchrony, with the result that bias remained constant. We suggest that separation fields did not become smaller and more dense with the contextual manipulation of Hisakata et al., but that the criterion number of separation fields was set as if this were the case. As a result, the sensitivity of separation discrimination did not vary with that contextual manipulation but the bias of separation discrimination did vary with that manipulation, in such a way that the separation between the test dots was underestimated.

In sum, we have demonstrated a novel effect of context on separation discrimination. The sensitivity of discrimination is greater when additional levels of separation are interleaved between the levels to be discriminated.

*Keywords:* separation, discrimination, separation discrimination, context effects, separation fields

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