Effect of depth on crowding investigated with a multi-depth plane display

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Abstract

Crowding occurs when highly visible objects are rendered unrecognizable in the presence of nearby features. Several studies have demonstrated that crowding can be reduced by depth differences between target and flanking features, which challenges the assumption of real-world significance because real objects typically occur at differing depths. However, most previous studies tested only small differences in depth and/or used standard stereo displays in which disparity, accommodation, and defocus blur are inconsistent with the real world. For this study we developed a multi-depth plane display consisting of three screens at different distances from the observer to test how crowding is affected by large, real differences in target-flanker depth. Overall, perceptual error decreased with increasing target-flanker spacing, but increased when the target or flankers were displayed at a different depth from fixation and one another. Our findings demonstrate that depth can increase crowding when depth differences are large. Analysis of the perceived appearance of the stimuli suggest that outside Panum's Fusional Area, crowding is increased by suppression to maintain single vision rather than by an increase in clutter because of diplopia. These findings suggest that crowding may be a more significant problem in real scenes than is estimated with 2D displays.

Introduction

Visual crowding is a phenomenon in which a peripherally viewed object, that is easily identifiable in isolation, becomes harder to recognize or identify when it is surrounded by other objects, despite still being clearly visible (Bouma, 1970; Herzog et al., 2015; Levi, 2008; Pelli, 2008; Whitney and Levi, 2011). There has been a tremendous amount of research on crowding and the topic has been extensively reviewed over the years (e.g., Herzog et al., 2015; Manassi and Whitney, 2018; Pelli, 2008; Strasburger et al., 2011; Whitney and Levi, 2011). This high level of interest is not surprising given that the natural environment is usually cluttered and mostly viewed in the peripheral visual field. Consequently, it is assumed that crowding has a large impact on our daily lives with implications for many everyday visual tasks including driving (Xia et al., 2020), reading (Legge, 2007) and face recognition (Kalpadakis-Smith et al., 2018; Louie et al., 2007). Crowding also has important clinical implications for people with central vision impairment (e.g., macular degeneration), amblyopia and dyslexia (Whitney and Levi, 2011). Through this body of research, we have been able to build a good understanding of what factors mediate and moderate crowding and develop unifying theories (Balas et al., 2009; Harrison and Bex, 2015; Keshvari and Rosenholtz, 2016).

However, despite the large body of literature, one area that remains surprisingly understudied is how crowding is affected by depth. This is important because we live in a three-dimensional environment and so to understand the significance of crowding in the real world it is essential to understand the role of depth information.

Kooi et al. (1994) were the first to investigate how depth influenced crowding. The authors found that compared to when a peripheral target and flankers were at the same depth, there was a release from crowding when the target and flankers were stereoscopically presented in crossed (front) and uncrossed (behind) disparities (Kooi et al., 1994). Sayim et al. (2008) found that when flankers were at fixation depth, there was less foveal crowding when the target was stereoscopically presented in front or behind the flankers. Felisberti et al. (2005) also found an effect of depth on crowding in the parafovea, but to a more limited extent. They reported a release from crowding in two out of three subjects when the target appeared behind the flankers, but only in one of the three subjects when the target was in front of the flankers (Felisberti et al., 2005). Astle et al. (2014) extended on previous research by testing the effect of depth on crowding over a range of stereoscopically produced target-flanker disparities (±800 arcsec). In line with previous studies, Astle et al. (2014) found that when the target was at fixation depth, increasing target-flanker disparity systematically reduced crowding. They also found that the release from crowding was asymmetric whereby crowding was greater when the flankers were in front of the target compared to behind it (Astle et al., 2014).

Taken together these studies appear to paint the picture that a difference in depth between a target and flankers reduces crowding. This challenges the assumption that crowding is a significant problem in three dimensional natural environments. However, the generalizability of these studies to the real world is arguably limited by the fact depth cues were generated stereoscopically. One potential problem with stereo displays is that disparity information often does not match with accommodation or defocus blur which can detrimentally effect depth

perception (Hoffman et al., 2008; Watt et al., 2005). Furthermore, all the above studies tested only small depth differences between target and flankers.

To our knowledge only three studies have investigated the effect of depth on crowding using a real depth display. All three studies used two orthogonally positioned screens viewed through a half-transparent mirror allowing stimuli to be displayed on two different depth planes simultaneously (Eberhardt and Huckauf, 2019, 2017, 2020). Unlike previous studies that investigated the effect of depth on crowding by varying the distance in depth between the target and flankers, Eberhardt and Huckauf (2017) kept the target and flankers at the same depth and presented them 0.06 diopters in front, behind or at the same depth as fixation. The authors found that this small difference in depth between the stimuli and fixation planes had no effect on the amount of crowding compared to when everything was presented at the fixation plane (Eberhardt and Huckauf, 2017). Eberhardt and Huckauf (2019) repeated and expanded on this work with the addition of a 'far' (± 0.1 diopter) depth difference between fixation and the stimuli in addition to the 'near' (± 0.06 diopter) condition. The results showed that the amount of crowding was greater when the stimuli were far from fixation compared to when they were near to fixation, regardless of whether the stimuli were in front or behind the fixation plane (Eberhardt and Huckauf, 2019). Most recently, Eberhardt and Huckauf (2020) used the same approach to investigate the effect of depth on crowding when the target and flankers were separated in depth. When flanker depth was varied while the target was at fixation depth, crowding increased with increasing target-flanker depth difference (Eberhardt and Huckauf, 2020). This result is the opposite to the findings of other studies in which small differences in depth between the target and flankers were introduced with stereoscopic disparity (Astle et al., 2014; Felisberti et al.,

2005; Kooi et al., 1994; Sayim et al., 2008). Furthermore, the authors also found that when flanker depth was varied while the target was at fixation depth, crowding was greater when the flankers were behind the target and fixation compared to in front of it (Eberhardt and Huckauf, 2020). When target depth was varied while the flankers were at fixation, there was more crowding when the target was in front of the flankers and fixation compared to when it was behind them (Eberhardt and Huckauf, 2020).

In light of the above discrepancies, there is a clear need for further research to improve our understanding of how depth information affects crowding. There is a particular need for studies that use real depth and that test large depth differences that reflect those experienced in the real world. Therefore, the aim of this study was to investigate the effect of real depth on crowding using a multi-depth plane display consisting of three screens at 0.4 m, 1.26 m, and 4 m.

Methods

Subject recruitment

A total of 110 naïve subjects were recruited from the Northeastern undergraduate population in exchange for course credit as compensation for their time. Of these, seven were excluded immediately following screening because they did not meet the inclusion criteria of normal or corrected-to-normal vision. An additional five subjects were excluded because of issues with the experimental code (N=3), calibration issues (N=1) or because they did not follow the task instructions (N=1). Thus, a total of 98 subjects (32 male, 66 female) contributed usable data across five separate experiments (22 in experiment 1, 19 in experiment 2, 21 in experiments 3 and 4, and 15 in experiment 5). All subjects read and signed an informed consent form approved

by the University Ethics Board before the experiment began. The experimental procedure was approved by the institutional review board at Northeastern University, and the experiment was performed in accordance with the tenets of the Declaration of Helsinki.

Setup

We developed a multi-depth plane display consisting of three screens at 0.4 m (near screen), 1.26 m (mid screen) and 4 m (far screen) from the observer (Figure 1). These distances were chosen because 4 m is close to optical infinity while 0.4 m is the clinical standard for near distance, with 1.26 m being in the middle of these two extremes in log units. For the far screen we used an ultra-short throw projector (Bomaker Polaris 4K Laser Projector) projected onto a 240 cm x 250 cm white wall at the end of the room. The mid and near screens were made from 101.5 cm x 76 cm and 46 cm x 36.5 cm clear 5mm acrylic respectively held in position by a frame constructed from extruded aluminum rails. The transparent acrylic was covered on one side with ClearBright transparent display film (Lux Labs Inc., Boston, MA, USA). This nanoparticle film enabled us to display images from two projectors (InFocus IN3116) onto the near and mid screens while preserving their transparency (Hsu et al., 2014), thus allowing observers to simultaneously view adjacent stimuli presented on all three depths planes at the same time. The screens were temporally synchronized and spatially aligned to ensure display timing and position were consistent across the three depth planes.

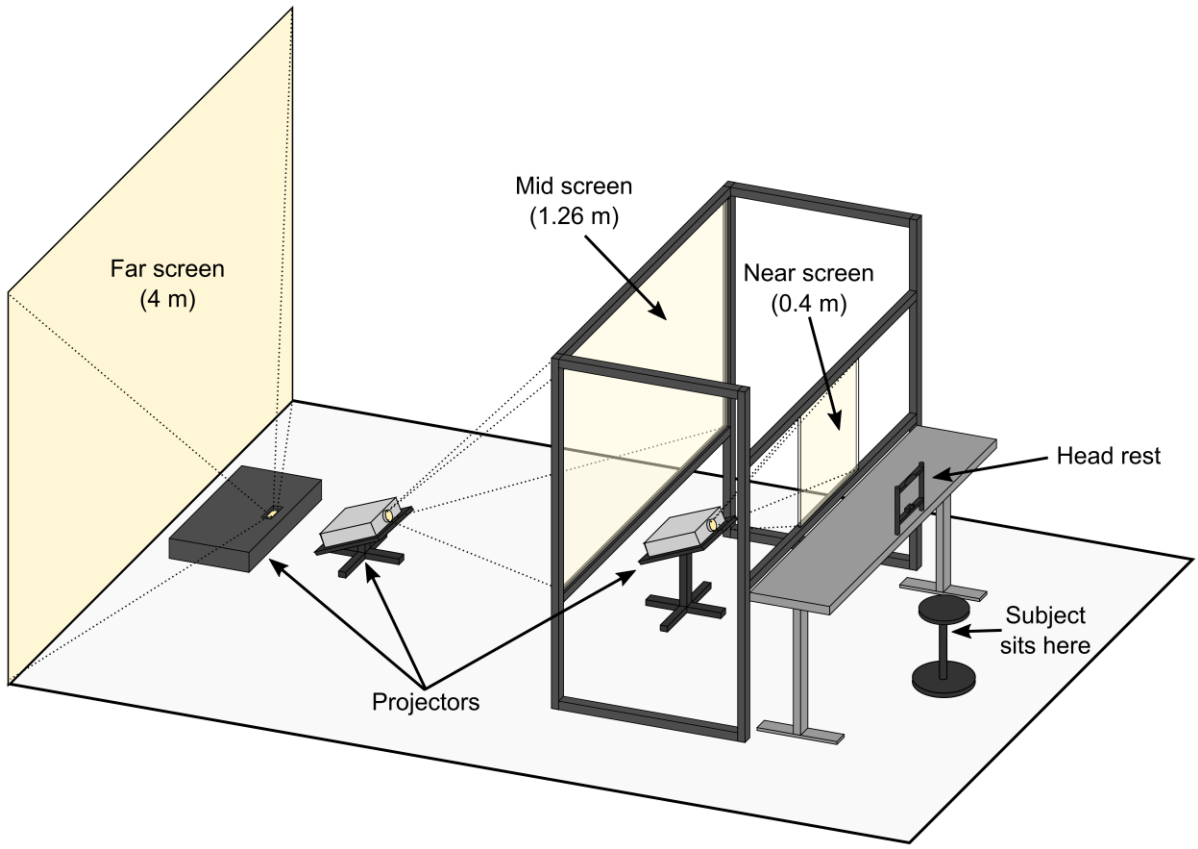

Figure 1: Illustration of the multi-depth plane display setup used for this study.

Spatial calibration

Each observer performed a subjective spatial calibration at the start of Experiments 1-4 to ensure that the angular positions of the stimuli and fixation point relative to primary gaze were the same (or as close as realistically possible) across all three depth planes. The center of the far screen (which was at primary gaze when the observers head was positioned in the chin and head rest) was used as the fixed reference against which all three screens were calibrated. With their head in the chin and head rest observers were instructed to sequentially position a series of targets so that they were in the same position as a fixed reference target that was displayed on the reference screen. The calibration was performed under monocular conditions using the observer's

dominant eye (determined by the Miles test). The calibration was performed monocularly because during a preliminary experiment subjects reported finding the task too difficult to complete under binocular conditions (e.g., because of diplopia, an issue that is considered further in the Discussion section). For Experiment 5, the spatial calibration was performed by the experimenter prior to the experiment using a webcam positioned at the observer's cyclopean point. Observers were asked to maintain the same head position within the chin and head rest throughout the experiment.

Stimuli and experimental conditions

The target and flankers were inspired by those used in previous studies (Harrison and Bex, 2017, 2015). The target was a white Landolt-C displayed against a black background at 10˚ eccentricity to the right or left of the fixation point at primary gaze. Following the structure of a Landolt-C optotype, the target was 1˚ in dimeter with a 0.25˚ line width and a 0.25˚ opening. The opening orientation of the target was random each trial, drawn from a uniform 360˚ distribution. The target was surrounded by a white flanker ring formed of four circular arcs (Figure 2). In each depth combination described below, the outer edge of the target was separated from the inner edge of the flanker ring by 5˚, 2.5˚, 1.25˚ or 0.625˚. These distances of separation represented 1/2, 1/4, 1/8 and 1/16 of the target eccentricity respectively. The line width and size of the four gaps in the flanker ring were kept constant (0.25˚). For each target depth, a control condition with no flanker ring was also included. The fixation point consisted of a 1˚ white circle with a black cross (Figure 2). This design was used because it has been reported to elicit more stable fixation compared to a plain circle or cross hair alone (Thaler et al., 2013). The background on all screens was always set to the lowest RGB (i.e. R=G=B=0) value which was transparent on

the near and mid screens, and black on the far screen. Since the mid screen was dimmest (R=G=B=255, white=13.56 cd/m^2), the luminance of stimuli displayed on the near and far screens were calibrated to match the luminance of the mid screen using a Photo Research PR-650 spectroradiometer (Photo Research, Chatsworth, CA, USA). The room lights were switched off for the duration of the experiment.

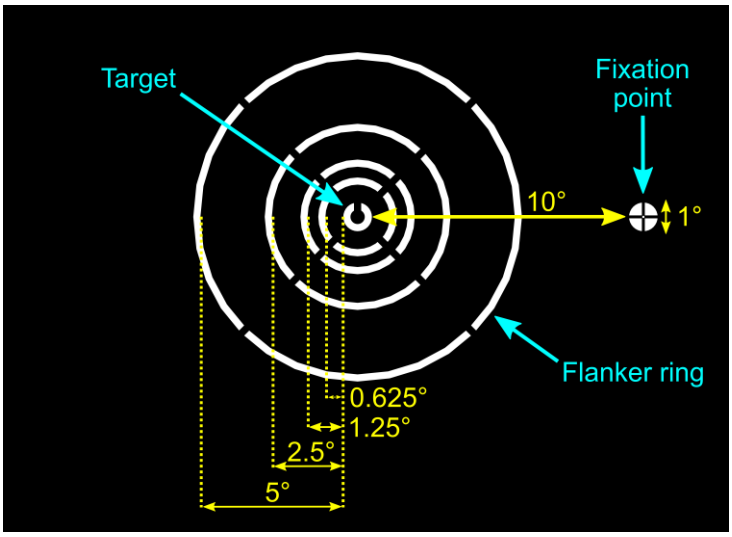

Figure 2: Schematic illustration of experimental stimuli and fixation marker. In all conditions, except the no-flanker condition, the randomly orientated target (a white Landolt-C) was surrounded by a white flanker ring at one of four possible target-flanker distances. The stimuli was viewed against a black background.

A summary of the stimulus conditions tested in each experiment is provide in Table 1. Briefly, in Experiments 1 and 2 the target was always presented at fixation depth while the depth of the flanker was varied. In Experiment 1 the target and fixation point were always on the mid screen while each flanker was displayed in front, behind or at fixation depth. In Experiment 2 the target and fixation point were presented on the near or far screen while the flanker was presented at one of the three depths across trials for each fixation distance. Experiments 3 and 4 were the same as Experiments 1 and 2 except that the flanker ring was presented at fixation depth while the target

depth was varied. In Experiment 3, the flanker and fixation point were always on the mid screen while the target was displayed on one of the three depth planes across trials. In Experiment 4, the flankers and fixation point were presented on the near or far screen while the target was presented at each of the three depths across trials for each fixation distance. For Experiment 5, the target, flanker ring and fixation were presented together on the same screen at three different fixation depths. This was to investigate whether there was an effect of absolute viewing distance on crowding when there was no depth difference between the target and flanker ring.

Table 1: Summary of the stimulus conditions in each experiment. The same color scheme is used to represent the near (0.4 m), mid (1.26 m) and far (4 m) screens throughout the manuscript. Note that for target-flanker spacing, 'infinity' = no flanker ring.

Experiment	Fixation depth (m)	Target depth (m)	Flanker depth (m)	Target-flanker spacing (degrees)	No. of stimulus conditions	Total no. presentations	Sample size
Exp 1	Mid (1.26)	Mid (1.26)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚	13	130 (10 reps per stimulus)	N = 22
	Mid (1.26)	Mid (1.26)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Mid (1.26)	Mid (1.26)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚			
Exp 2	Near (0.4)	Near (0.4)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity	26	260 (10 reps per stimulus)	N = 19
	Near (0.4)	Near (0.4)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚			
	Near (0.4)	Near (0.4)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚			
	Far (4)	Far (4)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚			
	Far (4)	Far (4)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚			
	Far (4)	Far (4)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
Exp 3	Mid (1.26)	Near (0.4)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity	15	150 (10 reps per stimulus)	N = 21
	Mid (1.26)	Mid (1.26)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Mid (1.26)	Far (4)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
Exp 4	Near (0.4)	Near (0.4)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity	30	240 (8 reps per stimulus)	N = 21
	Near (0.4)	Mid (1.26)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Near (0.4)	Far (4)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Far (4)	Near (0.4)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Far (4)	Mid (1.26)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Far (4)	Far (4)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
Exp 5	Near (0.4)	Near (0.4)	Near (0.4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity	15	150 (10 reps per stimulus)	N = 15
	Mid (1.26)	Mid (1.26)	Mid (1.26)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			
	Far (4)	Far (4)	Far (4)	0.625˚, 1.25˚, 2.5˚, 5˚, infinity			

Each condition was repeated 10 times in Experiments 1, 2, 3 and 5 and eight times in Experiment 4, with equal number of repeats on either side of the fixation point. The order of testing was randomized.

An example trial is illustrated in Figure 3. Briefly, at the start of each trial, observers were instructed to focus on the central fixation point. The fixation point appeared on the fixation screen 1 sec before stimulus onset in Experiments 1, 3 and 5, and 1.5 sec before stimulus onset in Experiments 2 and 4. The target and flanker ring (if present) were displayed for 0.25 sec. The fixation point remained on the screen for 1 sec before being replaced by a randomly oriented Landolt-C that was the same size as the target Landolt-C. The observer used the mouse to rotate this Landolt-C until it matched the perceived orientation of the target and then clicked to report the orientation. In all experiments except Experiment 5, the observer then reported the perceived location of the target relative to the position of the flanker ring. There were 5 options to choose from, “target in center of ring”, “target inside ring but not in the center”, “ring obstructs target”, “target outside ring”, and “unsure or no ring”. Observers were instructed to select the option that was the closest match to how they perceived the stimulus. If an observer missed the stimulus or they were unsure of the targets’ location relative to the flanker ring (e.g., because of diplopia) they were instructed to select the “unsure or no ring” option. Following this selection, the next trial started immediately. Before starting an experiment, all participants underwent training during which they were encouraged to complete as many practice trials as they needed to familiarize themselves with the task. These practice trials did not contribute to the collected data.

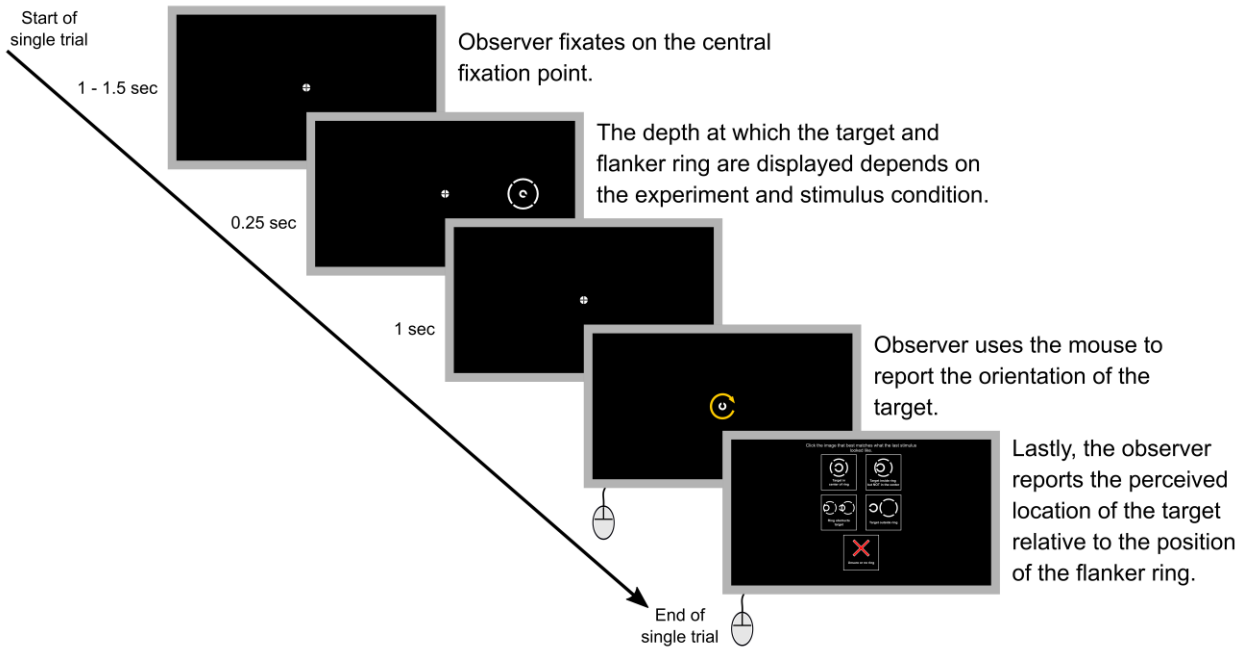

Figure 3: A step-by-step example of a single trial. Note that step five was not included in Experiment 5.

Data processing and statistical analysis

Perceptual error

To quantify crowding for each stimulus condition we first calculated the report error for each presentation, i.e., the angular difference between the reported gap orientation of the target and the actual gap orientation. For each subject, this generated 10 report errors per stimulus condition in Experiments 1, 2, 3 and 5, and eight per stimulus condition in Experiment 4. We then used these report errors to calculate the circular standard deviation for each stimulus condition using the Circular Statistics Toolbox (Berens, 2009) in MATLAB R2022a (MathWorks Inc., Natick, MA, USA). We refer to this measure as perceptual error, which is reported in degrees.

The effect of target/flanker depth and target-flanker spacing on perceptual error was analyzed using mixed effects multiple linear regression, fitted using the lme4 package (Bates et al., 2015) in R (R Core Team, 2022). Perceptual error was used as the response (dependent) variable after being natural log transformed to correct for positive skew. For all five experiments, we included target-flanker spacing as a fixed effect. We also included flanker depth for Experiments 1 and 2, target depth for Experiments 3 and 4 or target-flanker-fixation depth for Experiment 5. Target-fixation depth or flanker-fixation depth were also included as a third fixed effect for Experiment 2 and 4 respectively. All possible pairwise interactions of fixed effects were fitted in the full model. Subject identification (ID) was included as a random effect in all experiments to control for repeated measures. We first used model simplification, whereby models were compared with one another using a likelihood ratio test (LRT), to remove non-significant interactions sequentially. This enabled us to test the effect of individual fixed effects that were not involved in an interaction. We then used the minimum model (i.e., model containing all fixed effects of interest plus any significant two-way interactions) to report the significance of each main effect or important interaction(s) by using a LRT to compare the minimum model with the same model but with the effect/interaction of interest removed. Note that data for the control condition (i.e., no flanker ring) were excluded from statistical analysis. This was to ensure that a) the fixed effects remained independent and b) the effect of having no flanker ring did not mask any of the effects we were most interested in (see Supplementary Material for a more detailed explanation).

Perceived target position relative to flanker ring

For statistical analysis, the results for the perceived target position relative to the flanker ring were converted to a binary response. A value of 1 meant that the observer perceived the target as being inside the flanker ring (i.e., they chose either “target in center of ring” or “target inside ring but not in the center”) while a value of 0 meant the subject did not perceive the target as being inside the flanker ring (i.e., they chose “ring obstructs target”, “target outside ring” or “unsure or no ring”).

These data were then analyzed using mixed effects binary logistic regression, fitted using the lme4 package (Bates et al., 2015) in R (R Core Team, 2022). We used the DHARMa package (Hartig, 2022) to run residual diagnostics that are often overlooked in logistic regression. Perceived target position was used as the binary response variable (i.e., 1 = target inside ring and 0 = target not inside ring). The fixed effect, and pairwise interaction for each experiment were the same as those described above for the analysis of perceptual error. Subject ID was included as a random effect in all experiments to control for repeated measures. Model simplification (to remove non-significant interactions) and significance testing was the same as described above for the analysis of perceptual error. Data for the control condition (i.e., no flanker ring) were excluded from statistical analysis for the same reasons as those outlined above.

The separate results showing the number of times observers chose each of the five choices for perceived target position relative to the flanker ring can be found in the Supplementary Material (Figures S1-S4).

Results

Perceptual error

Target always at fixation depth with variable flanker depth

Experiment 1: Target and fixation at 1.26 m with flanker ring presented at each depth (Figure 4A). Perceptual error was higher when the flanker ring was displayed in front of, or behind, the target and fixation plane (mixed effects multiple linear regression models compared via LRT: $\chi^2_{(2)} = 20.67$, $p < 0.001$). As expected, perceptual error decreased as target-flanker spacing increased ($\chi^2_{(1)} = 31.71$, $p < 0.001$).

Experiment 2: Target and fixation at 0.4 m or 4 m with flanker ring presented at each depth (Figure 4B). Perceptual error tended to increase with increasing flanker depth when the flanker ring was behind the target and fixation plane, however, the effect of flanker depth was much weaker when the flanker ring was in front of the target and fixation (interaction between target-fixation depth and flanker depth: $\chi^2_{(2)} = 17.18$, $p<0.001$). Perceptual error decreased with increasing target-flanker spacing, in a manner corresponding to target-fixation depth (interaction between target-flanker spacing and target-fixation depth: $\chi^2_{(1)} = 9.2$, $p=0.002$).

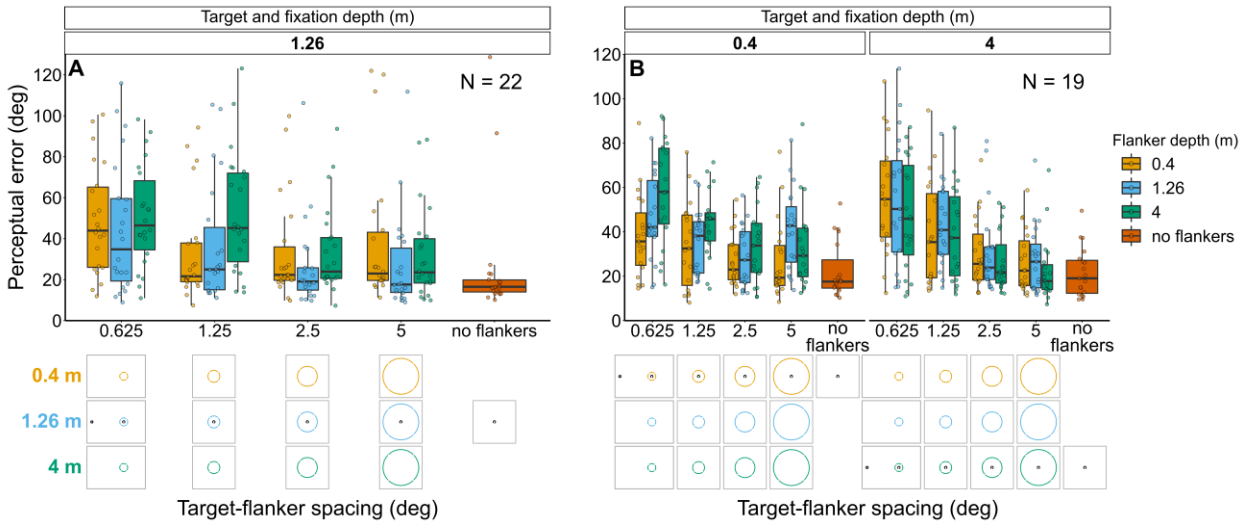

Figure 4: Perceptual error results for Experiments 1 (A) and 2 (B) in which flanker depth was varied while the target was always at fixation depth. Box plots show medians plus the interquartile range (IQR), whiskers are the lowest and highest values that are within 1.5 times the IQR from the upper and lower quartiles. Points show the perceptual error for each individual observer. The visual aid below each graph shows the depth of the flanker ring (based on the same color key as the box plot) relative to the depth of the fixation point and target (shown in black) for each stimulus condition. The relative sizes of, and distances between, the fixation point, target, and flanker ring are to scale. Note that the fixation point is only shown for the 0.625˚ target-flanker spacing due to limited space within the figure.

<u>Flanker ring always at fixation depth with variable target depth</u>

Experiment 3: Flanker ring and fixation at 1.26 m with target presented at each depth (Figure 5A). Overall, perceptual error was higher when the target was displayed in front of, or behind, the flanker ring and fixation ($\chi^2_{(2)} = 36.93$, $p < 0.001$), with the greatest perceptual error occurring when the target was behind the flanker ring and fixation. Perceptual error decreased as target-flanker spacing increased ($\chi^2_{(1)} = 45.99$, $p < 0.001$).

Experiment 4: Flanker ring and fixation at 0.4 m or 4 m with target presented at each depth (Figure 5B). Perceptual error was greatest when the target was displayed behind the flanker ring and fixation, while the effect of depth was less prominent when the target was displayed in front of the flanker ring and fixation (interaction between flanker-fixation depth and target depth: $\chi^2_{(2)} = 61.87$, $p<0.001$). Perceptual error decreased as target-flanker spacing increased ($\chi^2_{(1)} = 29.92$, $p<0.001$).

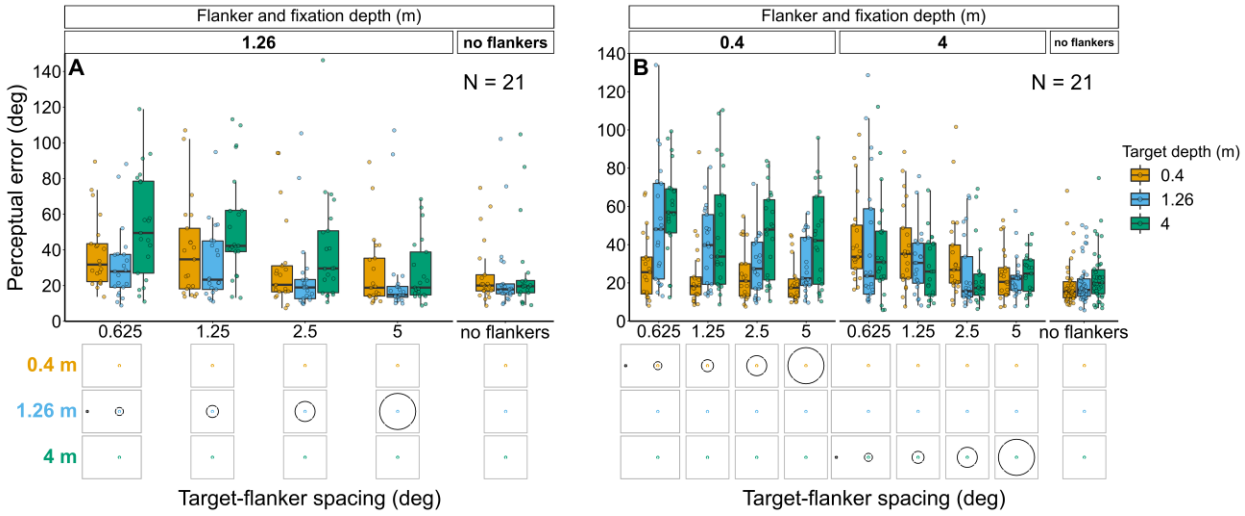

Figure 5: **Perceptual error results for Experiments 3 (A) and 4 (B) in which target depth was varied while the flanker ring was always at fixation depth.** Box plots show medians plus the interquartile range (IQR), whiskers are the lowest and highest values that are within 1.5 times the IQR from the upper and lower quartiles. Points show the perceptual error for each individual observer. The visual aid below each graph shows the depth of the target (based on the same color key as the box plot) relative to the depth of the fixation point and flanker ring (shown in black) for each stimulus condition. The relative sizes of, and distances between, the fixation point, target, and flanker ring are to scale. Note that the fixation point is only shown for the 0.625˚ target-flanker spacing due to limited space within the figure.

<u>Target and flanker ring at fixation depth</u>

Experiment 5: Target and flanker ring always at fixation depth (Figure 6). Perceptual error decreased as target-flanker spacing increased ($\chi^2_{(1)} = 64.8$, $p<0.001$). There was also a significant effect of depth ($\chi^2_{(2)} = 8.75$, $p=0.013$) resulting from a higher perceptual error for stimuli displayed at 4 m.

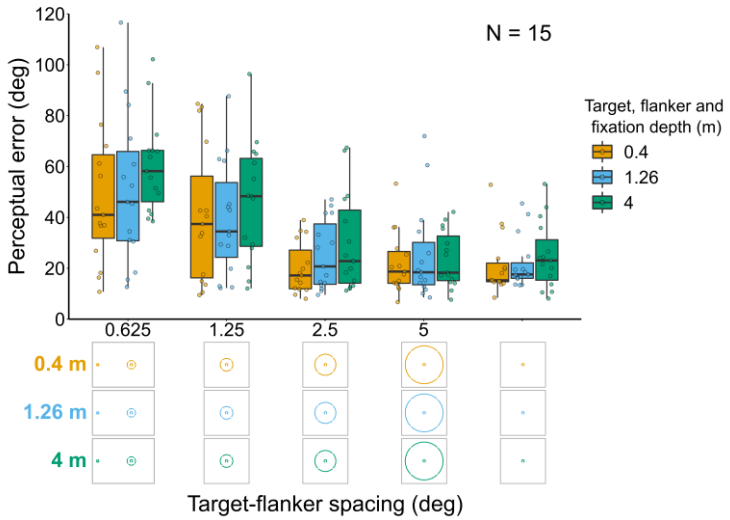

Figure 6: **Perceptual error results for Experiment 5 in which the target and flanker were always presented at the same depth as the fixation point.** Box plots show medians plus the interquartile range (IQR), whiskers are the lowest and highest values that are within 1.5 times the IQR from the upper and lower quartiles. Points show the perceptual error for each individual observer. The visual aid below the graph shows the depth of the target, flanker, and fixation point (based on the same color key as the box plot) for each stimulus condition. The relative sizes of, and distances between, the fixation point, target, and flanker ring are to scale. Note that the fixation point is only shown for the 0.625˚ target-flanker spacing.

Perceived target position relative to the flanker ring

<u>Target always at fixation depth with variable flanker depth</u>

Experiment 1: Target and fixation at 1.26 m with flanker ring presented at each depth (Figure 7A and supplementary Figure S1). In Experiment 1, most observers consistently reported seeing the target inside the flanker ring. However, when the flanker ring was away from target-fixation depth there was a reduction in the proportion of observers who consistently reported seeing the target within the flanker ring when the target-flanker spacing was small (mixed effects binary logistic regression models compared via LRT; interaction between target-

flanker spacing and flanker depth: $\chi^2_{(2)} = 36.12$, $p < 0.001$). This effect was greatest when the flanker ring was displayed behind the target and fixation.

Note that in all four experiments, the response to the control (i.e., no flanker condition) indicates the probability of an observer making an inaccurate report (e.g., they selected the wrong option by mistake or missed the stimulus and reported a guess rather than selecting the "Unsure" option).

Experiment 2: Target and fixation at 0.4 m or 4 m with flanker ring presented at each depth (Figure 7B and supplementary Figure S2). As with the previous experiments, when the flanker ring was away from target-fixation depth, there was a reduction in the overall proportion of trials in which observers reported seeing the target within the flanker ring (interaction between target-fixation depth and flanker depth: $\chi^2_{(2)} = 374.26$, $p < 0.001$). The greatest reduction occurred when target-flanker spacing was smaller ($\chi^2_{(1)} = 178.65$, $p < 0.001$).

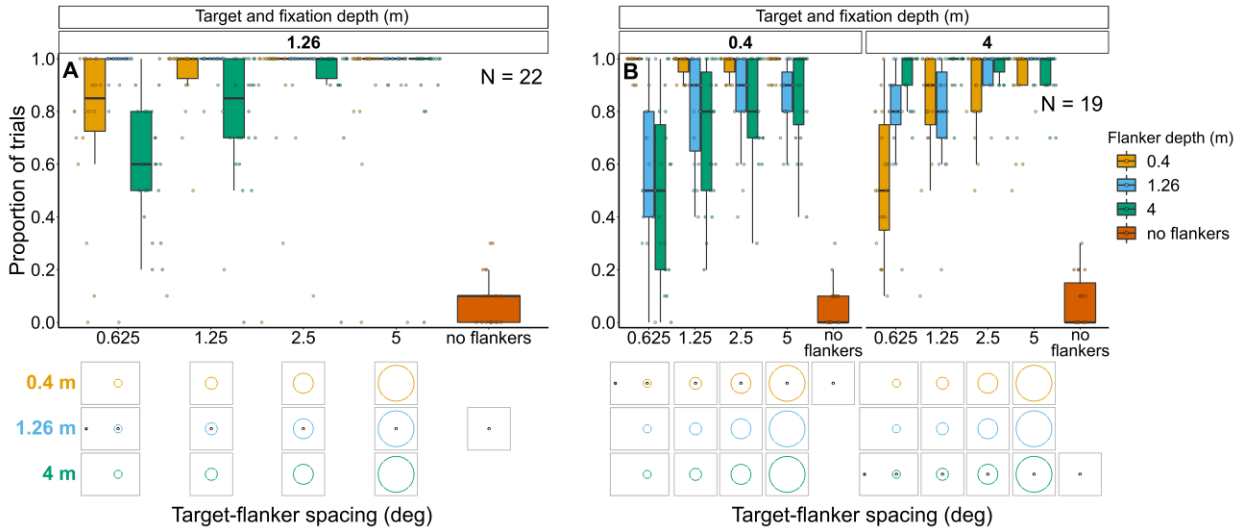

Figure 7: **Proportion of trials in which observers reported seeing the target inside the flanker ring for Experiments 1 (A) and 2 (B).** In both experiments flanker depth was varied while the target was

always at fixation depth**.** Box plots show medians plus the interquartile range (IQR), whiskers are the lowest and highest values that are within 1.5 times the IQR from the upper and lower quartiles. Points show the proportion of trials for each individual observer. The visual aid below each graph shows the depth of the flanker ring (based on the same color key as the box plot) relative to the depth of the fixation point and target (shown in black) for each stimulus condition. The relative sizes of, and distances between, the fixation point, target, and flanker ring are to scale. Note that the fixation point is only shown for the 0.625˚ target-flanker spacing due to limited space within the figure.

<u>Flanker ring always at fixation depth with variable target depth</u>

Experiment 3: Flanker ring and fixation at 1.26 m with target presented at each depth (Figure 8A and supplementary Figure S3). When the target was away from flanker-fixation depth, observers were less likely to report seeing the target within the flanker ring. This effect was greatest when target-flanker spacing was smaller and when the target was displayed in front of the flanker ring and fixation (interaction between target-flanker spacing and target depth: $\chi^2_{(2)} = 100.38$, $p < 0.001$).

Experiment 4: Flanker ring and fixation at 0.4 m or 4 m with target presented at each depth (Figure 8B and supplementary Figure S4). As with the previous experiment, the greater the difference between target depth and flanker-fixation depth, the less likely observers were to report seeing the target within the flanker ring (interaction between flanker-fixation depth and target depth: $\chi^2_{(2)} = 779.49$, $p < 0.001$), particularly when target-flanker spacing was small (interaction between target-flanker spacing and target depth: $\chi^2_{(2)} = 23.27$, $p < 0.001$). However, target-flanker spacing had a weaker effect on the proportion of trials in which observers reported seeing the target within the flanker ring when the flanker ring and fixation were near compared to far (interaction between target-flanker spacing and flanker-fixation depth: $\chi^2_{(1)} = 56.23$, $p < 0.001$).

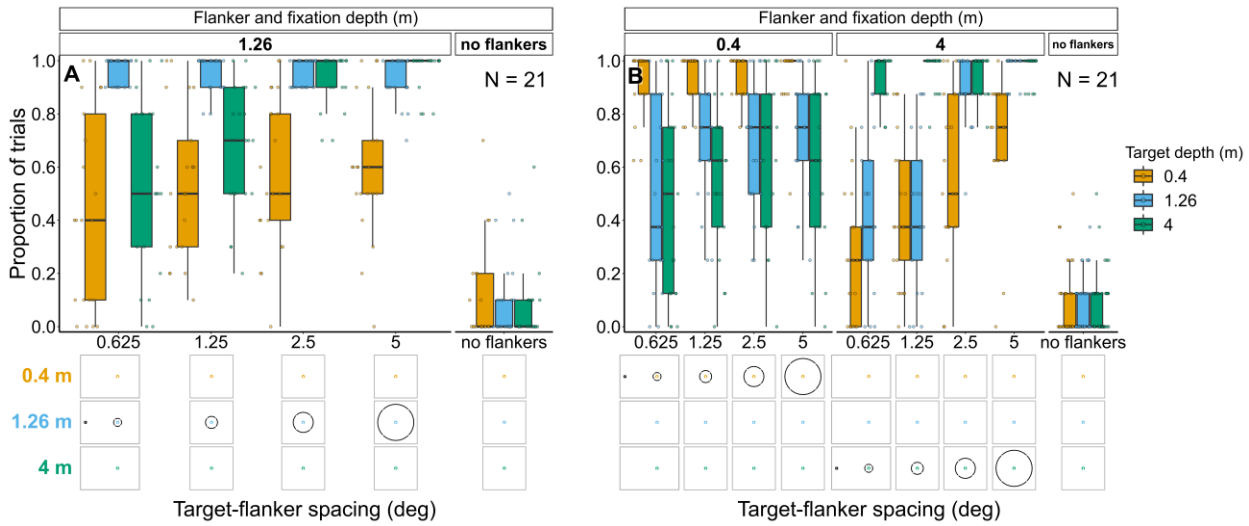

Figure 8: **Proportion of trials in which observers reported seeing the target inside the flanker ring for Experiments 3 (A) and 4 (B).** In both experiments target depth was varied while the flanker ring was always at fixation depth**.** Box plots show medians plus the interquartile range (IQR), whiskers are the lowest and highest values that are within 1.5 times the IQR from the upper and lower quartiles. Points show the proportion of trials for each individual observer. The visual aid below each graph shows the depth of the target (based on the same color key as the box plot) relative to the depth of the fixation point and flanker ring (shown in black) for each stimulus condition. The relative sizes of, and distances between, the fixation point, target, and flanker ring are to scale. Note that the fixation point is only shown for the 0.625˚ target-flanker spacing due to limited space within the figure.

Discussion

In all experiments, perceptual error decreased as the target-flanker spacing increased, which is in line with previous crowding research (Bouma, 1970; Pelli, 2008). Overall, perceptual error was higher when the target or flanker ring were presented at a different depth from the other and from fixation. The greatest differences in perceptual error among the different depth conditions occurred when the target or flanker ring were presented behind fixation depth. In contrast, when the target or flanker ring were presented in front of fixation depth, the differences in perceptual error among depth conditions were notably smaller. The results also show that

when the target, flanker ring and fixation were all at the same depth plane, crowding tended to increase with the absolute distance of the stimuli from the observer.

The main finding that a depth difference between the flankers and the target led to an increase, rather than a decrease, in perceptual error is different from the findings of several previous studies that investigated the effect of depth on crowding using a stereoscopic presentation (Astle et al., 2014; Felisberti et al., 2005; Kooi et al., 1994; Sayim et al., 2008). For example, Astle et al (2014) found that when the target was presented at fixation depth (comparable to Experiments 1 and 2 in our study), increasing the disparity between the target and flankers resulted in less crowding, and ultimately a complete release from crowding. The authors also reported that crowding was greater when flankers were presented in crossed disparity (in front of the target and fixation), compared to uncrossed disparity (behind the target and fixation) (Astle et al., 2014). Similarly, when the flankers were presented at fixation depth (comparable to Experiments 3 and 4 in our study), Sayim et al (2008) found that foveal crowding was lower when the target was presented in front of or behind the flanker and fixation.

Several explanations for crowding have been proposed in which crowding occurs because target and flanking features are inappropriately grouped (Banks et al., 1979; Pachai et al., 2016). Consistent with this explanation, crowding can be alleviated when the flankers are grouped together and segmented from the target (Herzog and Manassi, 2015). One piece of evidence in support of this account is the reduction of crowding that can occur when flankers are presented at a different depth from the target (Astle et al., 2014; Felisberti et al., 2005; Kooi et al., 1994; Sayim et al., 2008). Our results challenge this view of crowding because it would predict that

increasing the depth difference between a target and flankers would decrease the probability of the flankers being grouped and increase the probability of their being segmented from the target, thereby decreasing crowding, the opposite of our finding. Other models of crowding, such as texture processing (Balas et al., 2009; Freeman and Simoncelli, 2011; Parkes et al., 2001; Wallis and Bex, 2012), sampling errors (Ester et al., 2015, 2014; Harrison and Bex, 2017, 2016, 2015), attentional resolution limits (He et al., 1996) or saccade properties (Nandy and Tjan, 2012) are agnostic concerning the influence of depth differences among targets and flankers. Therefore, each of these models would require modification to explain the increase in crowding that we observe with large real depth differences between a target and its flankers.

In contrast with studies that controlled depth with small stereoscopic disparities, our results do agree with the findings of Eberhardt and Huckauf (2020) who also used a real-depth display and tested larger differences in depth between the target and flankers than previous studies had examined. When the target was at fixation depth (comparable to Experiments 1 and 2 in our study), Eberhardt and Huckauf (2020) found that crowding increased with increasing target-flanker depth difference. The authors also found that crowding was greater when the flankers were behind the target and fixation compared to in front of it (Eberhardt and Huckauf, 2020). Our findings from Experiments 1 and 2 are consistent with these results. However, when the flankers were at fixation depth (comparable to Experiments 3 and 4 in our study), Eberhardt and Huckauf (2020) found that crowding was higher when the target was in front of the flankers and fixation compared to when it was behind them. In contrast, in Experiments 3 and 4 we found that perceptual error was greatest when the target was presented behind the flanker ring and fixation rather than in front of it. This difference may be due to a combination of defocus blur

when the target was behind fixation combined with the finding from Experiment 5 which found that in our study the absolute distance from the observer resulted in higher perceptual error.

Why the inconsistencies across studies? It is important to consider that most of the previous studies used very small depth differences, the largest being 0.1 diopters in Eberhardt and Huckauf (2020) and Eberhardt and Huckauf (2019). In comparison, the depth difference in our study ranged from 0.54 diopters (between the mid and far screens) to 2.25 diopters (between the near and far screens). This difference has several implications that may help to explain the results. It is possible that small differences in depth between the target and flankers reduce crowding (Astle et al., 2014; Felisberti et al., 2005; Kooi et al., 1994; Sayim et al., 2008), while larger differences in depth increase it (Eberhardt and Huckauf, 2020; and results from our study) and models of crowding will simply have to accommodate this peculiar property. Although this pattern is quite surprising, there is precedent for non-linear effects of depth on perceptual processing outside the crowding literature. In a multiple object tracking task, when the targets and distractors were distributed equally on two depth planes, tracking accuracy was better than the accuracy during trials in which targets and distractors appeared on a single depth plane when the depth difference between planes was small (~6 cm) (Ur Rehman et al., 2015; Viswanathan and Mingolla, 2002), but worse when the depth difference between planes was large (50 cm) (Ur Rehman et al., 2015).

How could depth affect perception in this nonlinear way? The geometry of the eyes and the 3D environment create interocular disparity differences between the images in each eye. When corresponding features in the images in each eye can be identified, the images can be

fused to generate a binocular perceptual experience of depth (for review see Nityananda and Read, 2017)). There is a horizontal and vertical spatial limit to the interocular disparity difference over which the visual system attempts to identify corresponding retinal points in order to fuse different 2D interocular images as a single 3D object (Westheimer, 1979). This 2D spatial correspondence limit creates a 3D volume along the horopter known as Panum's Fusional Area (Panum, 1858). Outside Panum's Fusional Area, there is a loss of stereoscopic depth perception and either double vision (diplopia) may be experienced, or single vision may occur if the image from one eye is suppressed (Georgeson and Wallis, 2014; Ono et al., 1977). The spatial scale of Stereoscopic Panum's Fusional Area depends on the spatial frequency of the stimuli (Maiello et al., 2020; Pulliam, 1981; Reynaud and Hess, 2017; Wilcox and Allison, 2009; Yang and Blake, 1991) and increases with eccentricity (Hampton and Kertesz, 1983; Qin et al., 2006). It is possible that differences between fusion and depth perception within Panum's Fusional Area and diplopia or suppression outside of it, may explain the patterns of results observed between studies. Small stereoscopic disparity differences between target and flankers create differences in perceived depth that can alleviate the effects of crowding, potentially through grouping (Herzog and Manassi, 2015) or by independent processing of target and flankers in different depth-selective channels (Norcia et al., 1985; Pulliam, 1981; Reynaud and Hess, 2017; Tyler et al., 1994; Wilcox and Allison, 2009; Yang and Blake, 1991) by any of the computational models of crowding based on texture processing (Balas et al., 2009; Freeman and Simoncelli, 2011; Parkes et al., 2001; Wallis and Bex, 2012), sampling errors (Ester et al., 2015, 2014; Harrison and Bex, 2017, 2016, 2015) attentional resolution limits (He et al., 1996) or saccade properties (Nandy and Tjan, 2012). Large interocular disparity differences may induce diplopia or suppression that could increase perceptual error by increasing the number of features (diplopia) or removing the

benefit of binocular summation (suppression) that can help decrease the effects of crowding (Siman-Tov et al., 2021).

In this study, when asked, only a few observers reported experiencing diplopia, and those that did, reported only experiencing it in a minority of presentations for which they selected the 'unsure or no ring' option when reporting the perceived location of the target. As mentioned in the Methods sections, observers did report experiencing diplopia when trying to perform the spatial calibration task under binocular conditions during a pilot experiment. However, it should be noted that the spatial calibration required observers to simultaneously concentrate on stimuli at two different depths for an extended length of time. The calibration is therefore a fundamentally different task from our crowding experiments in which stimuli were only briefly presented in the observer's peripheral visual field, which could explain why few observers reported diplopia in the main experiments. If the image from one eye were partly suppressed to prevent diplopia, the reported location of the target relative to the flanker ring offers us potential clues as to which eye was likely being suppressed. For instance, assuming no head movement following the spatial calibration performed using the dominant eye, for presentations in which the observer reported that the target was inside the flanker ring, it's likely that it was the image from the non-calibrated eye that was suppressed. Conversely, if the observer reported seeing the target outside the flanker ring, or that the target was obscured by the edge of the flanker ring, then this would instead imply it was the image from the calibrated eye that was being suppressed. However, as well as suppression of the calibrated eye, a perceived misalignment of the target and flanker ring could also mean that the observer didn't maintain the same head position as they had during the calibration. Although a chin and head rest were used to ensure the

observer maintained a steady head position throughout the experiment, it remains possible that small head movements did occur. Furthermore, the larger the depth difference between the target and flanker ring, and the smaller the target-flanker spacing, the more sensitive the spatial calibration would have been to changes in head position. Indeed, Figures 7 and 8 show that when either the target or flanker ring were away from fixation depth, participants reported seeing the target in the center of the flanker ring on fewer trials when the target-flanker spacing was small.

Given that observers were less likely to perceive the target inside the flanker ring when the target and flanker ring were separated by depth, one explanation for the higher perceptual error could be perceptual occlusion of the target by the flanker ring. To examine how the trials in which observers reported that the target was not inside the flanker ring (i.e., target obstructed ring, target was outside ring, or they were unsure) affected the overall results, we recalculated perceptual error using only trials in which the observer reported seeing the target inside the flanker ring (supplementary Figures S5 and S6) and reanalyzed these data the same way as for perceptual error calculated from the full data set. Apart from Experiment 2, the effect of flanker and/or target depth remained statistically significant (see supplementary material for analysis results) meaning that across the majority of experiments misalignment or occlusion of the target by the flanker ring is not enough to explain the overall results. This can be seen visually by comparing Figures 4 and 5 with their corresponding figures in the supplementary material (Figures S5 and S6 respectively).

Our findings do not support the widely held view that depth differences between targets and flankers always reduces crowding, instead the effect of depth on crowding appears to be more complex than originally assumed. Our results, alongside those of previous studies, suggest

that small differences in depth between targets and flankers do not have the same effect on crowding as larger differences in depth in which either the target or flankers are presented outside the limits of Panum's Fusional Area. We suggest that large differences in depth between target and flankers can increase crowding because of suppression to maintain single vision as this removes the benefits of binocular summation. This property confirms the importance of crowding in natural scenes.

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Author Contributions

S.P.S. and P.J.B. conceived the study and the idea of the multi-depth plane display and designed the experiments. S.P.S. designed and built the multi-depth plane display, wrote all code, and performed analyses. S.P.S., Y.S., and J.A. conducted the experiments. S.P.S. and P.J.B. wrote the manuscript with input from all authors.

Data Availability

All data and code required to replicate the analyses in this paper will be made available on an online repository at the stage of publication. It will also be made available to reviewers during peer review.

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