

Orientation categories used in guidance of attention in visual search can differ in strength

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Abstract We investigated orientation categories in the guidance of attention in visual search. In the first two experiments, participants had a limited amount of time to find a target line among distractors lines. We systematically varied the orientation of the target and the angular difference between the target and distractors. We find vertical, horizontal, and 45° targets require the least target/distractor angular difference to be found reliably and that the rate at which increases in target/distractor difference decrease search difficulty to be independent of target identity. Unexpectedly, even when the angular difference between the target and distractors was large, search performance was never optimal when the target orientation was 45°. A third experiment investigates this unexpected finding by correlating target/distractor difference and error rate with performance on tasks that measure a specific perceptual or cognitive ability. We find that the elevated error rate is correlated with performance on stimulus recognition and identification tasks, while the amount of target/distractor difference needed to detect the target reliably is correlated with performance on a stimulus reproduction task. We conclude that the target/distractor difference reveals the number of orientation categories in visual search, and, accordingly, that there are four such categories: two strong ones centred on 0° and 90° and two weak ones centred on 45° and 135°.

Keywords Visual search · Attention · Linear separability

Early visual search theorists believed that visual search provided an easy investigation of early visual features (Julesz & Bergen, 1983; Treisman & Gelade, 1980). Since orientation had long since been recognised as a low-level feature of vision, resolved in the early visual cortex (Hubel & Wiesel, 1974), the topic of how visual search for orientation was performed was investigated at length. Visual search for displays defined by orientation was found to be performed quickly and efficiently (Bergen & Julesz, 1983) as well as exhibiting search asymmetry (i.e., where search for a certain target amongst certain distractors was faster than if the target and distractor identities were swapped; Treisman & Gormican, 1988), two factors that were originally thought of as diagnostic of being an early visual feature. The convergence of the visual search results with what was already known from the neurophysiological literature led some researchers to believe that it was thus possible to model visual systems using behavioural data from visual search. For example, Foster and Ward (1991) conducted an exhaustive set of experiments on visual search asymmetries in orientation, comparing search performance on displays with targets that ranged from 0° to 180° (in steps of 22.5°) amongst distractors that also ranged from 0° to 180°. From the data, they theorised the existence of two orientation tuning functions centred on 90° and 180°, with a width of about 31° to 32°.

Unfortunately, Foster and Ward's (1991) work coincided with the backlash against the theory that visual search could be used to investigate early visual features. Efficient search and search asymmetries for displays defined by features that could not conceivably be resolved in the early visual system began to surface, for example, familiarity (Wang, Cavanagh, & Green, 1994), 3-D structure (Enns & Rensink, 1990), and

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binocular disparity (He & Nakayama, 1992). One reaction to this was the idea that visual search was not allowing us to investigate early features but features that the attentional system could use for guidance (Wolfe & Horowitz, 2004, 2017). These features would thus contain categories that could be activated to cue attention to items that were included in that category (Wolfe, 1994, 2007). In the area of orientation, Wolfe, Friedman-Hill, Stewart, and O'Connell (1992) theorised that there were four categories of orientation, centred on the cardinal and oblique angles of 0°, 45°, 90°, and 135°. However, two problems exist in the interpretation of their data.

The first problem is that the evidence for a channel centred on 45° is weak. Search for a 45° target amongst -45°, 0°, and 90° distractors was found not to be efficient. The authors put this down to mirror confusion (Wolfe & Friedman-Hill, 1992) but did not include a condition that would have avoided mirror confusion (e.g., a 45° target amongst -30°, 0°, and 90° distractors). The second problem is that the existence of a phenomenon known as linear separability was not widely acknowledged at the time, and as such, a critical experiment in the study is confounded. Linear separability refers to the phenomenon where visual search is difficult if, when the display elements are plotted along the relevant dimension, the target lies within the range defined by the distractor values. Figure 1b and d illustrate two difficult search tasks, as the target is not linearly separable from the distractors. In contrast, search is much easier if the target and distractors can be separated by a single demarcation point along the dimension (Bauer, Jolicoeur, & Cowan, 1996; D'Zmura, 1991). An example of linearly separable displays is shown in Fig. 1a and c. The phenomenon of linear separability is particular relevant to the Wolfe et al. (1992) study because the critical evidence for a category centred on 45° was an experiment where search for a -30° target amongst 10° and 90° distractors was efficient, but search for a -20° target amongst 20° and -80° distractors was not. As they note, one display is a rotation of the other, but due to the orientation space wrapping around at 180° (Wolfe, Klempen, & Shulman, 1999), the first display is linearly separable (e.g., through a demarcation at -20°), whereas the second display is not. Given the weak evidence for a channel centred on 45°, it may be that Foster and Ward's (1991) original conception of two categories was correct.

Admittedly, the latter criticism hinges on the phenomenon of linear separability being real. Evidence for its existence is strong; it was originally found when representing colours on a CIE colour space (D'Zmura, 1991) and later confirmed using a more perceptually uniform colour space, CIELUV (Bauer et al., 1996). It has since been found in displays defined by shape (Arguin & Saumier, 2000) and size (Hodsoll & Humphreys, 2001). On the other hand, Vighneshvel and Arun (2013) have argued that linear separability is not an effect in its own right. Instead, they suggest it is merely a

product of three findings: target/distractor similarity, distractor/distractor similarity, and a nonlinear perceptual space. And, accordingly, they argue that there is no categorical difference between search performance on linearly separable and linearly inseparable displays. Given the wealth of evidence behind the effect of linear separability, regardless of its cause, the evidence for an orientation category centred at 45° appears weak.

To address the question of whether or not an orientation category centred on 45° exists, this study will investigate visual search for orientation in heterogeneous displays. We will systematically vary the target and distractor orientations, and measure search performance at each step. To control for possible effects of linear separability, all displays in the present study are linearly inseparable. If four categories of orientation (0°, 45°, 90°, and 135°) can be used to guide attention in visual search (Wolfe et al., 1992), then we should find that performance is best when the target is 0°, 45°, and 90°, but not at intermediate orientations. Otherwise, we should find that performance is best when the target is 0° and 90° (Foster & Ward, 1991).

Experiment 1

In this experiment, we investigate visual search for orientation by systematically varying the orientation of the target and the distractors. To do this, we test five different target orientations (0°, 15°, 45°, 75° and 90°; 0° is vertical, positive is clockwise) amongst distractors with an orientation of $\pm 7.5^\circ$ to $\pm 75^\circ$ from the target orientation. A notch was presented on 50% of the elements in the display (see Fig. 2a for an example display). The search display was shown for 1 second, and participants were asked to find the target line. When the display disappeared, participants reported (unspeeded) whether the target line contained a notch or not. Performance should be best when the target aligns with the centre of an orientation category.

Method

Participants Fifteen participants (nine females, mean age = 20.7 years, range: 19–23) took part in this experiment. Participants had normal or corrected-to-normal vision. All participants were naïve as to the purpose of the experiment.

Apparatus and stimuli The stimuli were generated in MATLAB using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al, 2007; Pelli, 1997). They were displayed on a 19-in. DiamondDigital CRT monitor (100 Hz refresh rate, 1024 × 768 pixels). A 57-cm long black tube was placed in front of the monitor, through which the participants looked. This tube was used to remove any objective vertical or

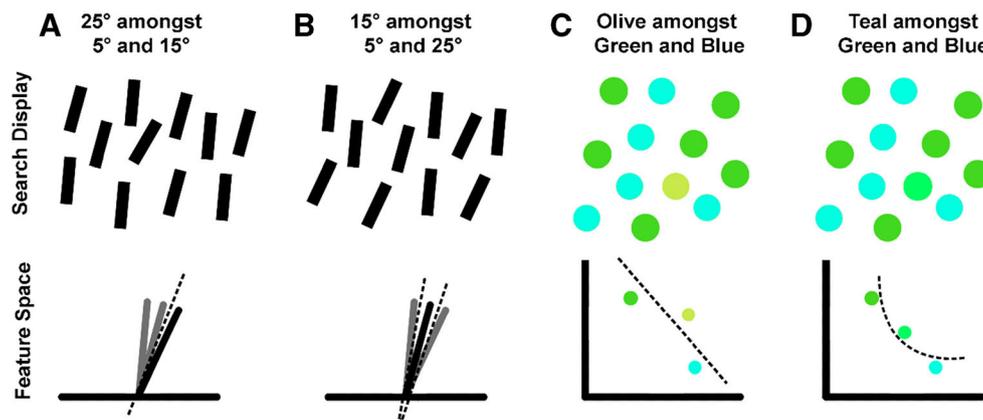


Fig. 1 Example of linearly separable (a and c) and linearly inseparable (b and d) displays. The *bottom row* represents the features present in the visual search displays above. The *dashed line* represents the demarcations needed to separate the target from the distractor. In a one-dimensional feature, such as orientation, a display is linearly separable if a single demarcation can separate the target from the distractors (as in a). If it

requires two demarcations, then it is linearly inseparable (as in b). In a multidimensional feature, such as colour, a display is linearly separable if it requires a single linear demarcation to separate the target from the distractor (as in c). If it requires multiple, or a nonlinear demarcation, then it is linearly inseparable (as in d). (Colour figure online)

horizontal from their vision. Participants used a standard keyboard to respond.

The stimulus consisted of a fixation dot (0.5° in diameter; 100 cd/m^2) and 24 lines, presented on a 5×5 grid, subtending an overall visual angle of 8° in height and width, as shown in Fig. 2a. The target line (1° in length, 0.2° in width, 100 cd/m^2) was one of five orientations: 0° , 15° , 45° , 75° , or 90° . Distractor lines were the same in all aspects to the target line, except that their orientation was plus or minus a set value from the target. This value ranged from $\pm 7.5^\circ$ to $\pm 75^\circ$ in steps of 7.5° , creating 10 distractor orientation sets. Note that there were always two different distractor orientations within a search display (e.g., 7.5° and -7.5° from the target orientation, but no other distractor orientations). Both target and distractor

lines were Gaussian blurred across their narrow dimension so that they blended into the background, avoiding staircase-like pixel artefacts along their length that could be used to identify orientation. Each line had a 50% chance of being bisected by a 0.1° “notch”. The distance from the centres of two adjacent lines was on average 1.7° , but the centres were jittered at random by up to 0.6° . The background of the screen was grey (11.05 cd/m^2) and kept constant during the experiment.

Design and procedure Each trial began with the presentation of a white fixation dot at the centre of the screen for 500 ms. The search display was then presented for 1,000 ms, followed by a blank screen. Participants were instructed to search for the target line and indicate the presence or absence of a notch in that line by pressing the right or left arrow, respectively, once the display disappeared. On 50% of the trials a notch was present in the target line, and on the remaining trials a notch was absent. After the participant’s response, the fixation cross would reappear, and after another 500 ms the subsequent trial was initiated. Participants completed five sessions of 250 trials, consisting of 25 trials for each of the 10 distractor orientation sets. Each session tested only one target orientation. Participants had the opportunity to take a break every 40 displays. Each condition was preceded by a practice block of 120 trials (12×10 distractor orientation sets) to get familiar with the task and target orientation.

Results and discussion

We analysed the results by plotting each participant’s accuracy as a function of the angular difference between the target and the distractors (see Fig. 3a). These data were then fitted with cumulative Gaussians psychometric functions using maximum likelihood estimation. The mean (μ), standard deviation

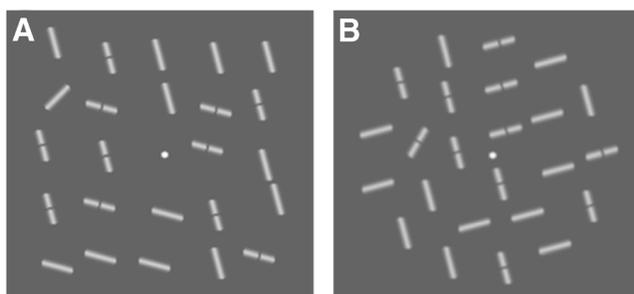


Fig. 2 Example search displays for Experiments 1 and 2. Displays consisted of 23 distractor lines and a target. Participants responded to the absence or presence of a notch in the target. **a** Search display for Experiment 1. The target’s orientation was fixed during each block, at 0° , 15° , 45° , 75° , or 90° (45° here). Half the distractors had an orientation clockwise from the target orientation. The other half of the distractors had an orientation of the same magnitude anti-clockwise from the target. The magnitude of this orientation was 7.5° to 75° from the target, varying from trial to trial. **b** Search display for Experiment 2. Same as **a**, but the target’s orientation was fixed at 0° , 15° , 30° or 45° depending on the condition (30° here). Note that the lines here are arranged around three imaginary circles centred on fixation

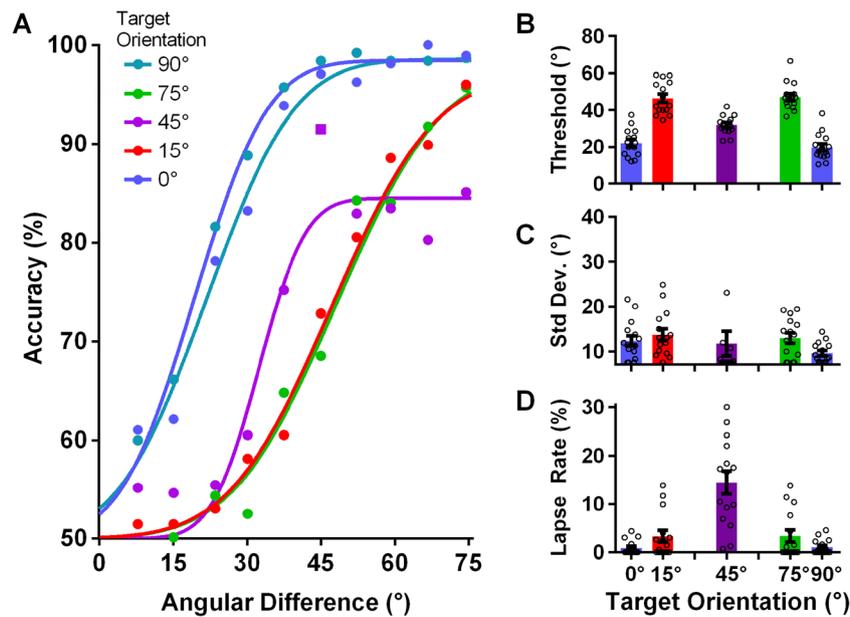


Fig. 3 Results for Experiment 1. **a** Average accuracy across all participants as a function of angular difference (target orientation vs. distractor orientation) for each target orientation. Continuous lines represent the best fitted psychometric curves. **b–d** Average threshold,

standard deviation and lapse rate parameters after fitting each participant’s data to a psychometric curve. *Error bars* represent ± 1 standard error of measurement. (Colour figure online)

(σ), and upper asymptote (λ) of the functions were free to vary (see Equation 1). The lower asymptote was fixed at 50% (i.e., chance level).

$$f(x) = \frac{1.5-\lambda}{2} + \frac{0.5-\lambda}{2} \left(\operatorname{erf} \left(\frac{x-\mu}{\sqrt{2}\alpha} \right) \right). \quad (1)$$

In the context of the experiment, the mean represents the threshold, or the angular difference at which performance was halfway between the upper and lower asymptotes. The standard deviation (σ) is a measure of the rate at which accuracy increases as angular difference between target and distractor increases, where a higher standard deviation is a slower rate. The upper asymptote represents the lapse rate, which is the proportion of errors after accounting for angular difference between the target and the distractors.

The mean threshold for each target orientation is shown in Fig. 3b. These were compared using a repeated-measures ANOVA procedure. There was a significant effect of target orientation, $F(4, 56) = 56.763, p < .001$. Bonferroni-corrected pairwise contrasts were run to understand this effect. The threshold for the 0° and 90° targets were found to be significantly lower than for 15°, 45°, and 75° targets, smallest $t(14) = 7.91$, largest $p = .005$; however, the difference in threshold between 0° and 90° was not significant, $t(14) = .060, p = 1.000$. The 45° target was found to have a lower threshold than the 15° and 75° targets, smallest $t(14) = 5.65$, both $ps < .001$. These contrasts indicate that the vertical and horizontal targets required the least amount of angular difference to be

reliably found, and the 15° and 75° targets required the most. On the face of it, the data seems to support the idea that there are four orientation categories, centred at 0°, 45, 90°, and 135° (Wolfe, 1994; Wolfe et al., 1992), with the addition that the channel centred on 45° (and presumably 135°) is less defined than channels centred on 0° and 90°.

The mean standard deviation for each target orientation is shown in Fig. 3c. These were also compared using a repeated-measures ANOVA procedure, which found no effect of target orientation on standard deviation, $F(4, 56) = .858, p = .495$. This suggests the performance increase due to increased angular difference is constant for all targets. That said, there is one outlying data point which could indicate an exception to this rule, as indicated by the purple square in Fig. 3a, occurring when the target is 45° and the distractors are both vertical and horizontal.

The mean lapse rate for each target orientation is shown in Fig. 3d. These were also compared using a repeated-measures ANOVA procedure. There was a significant effect of target orientation, $F(4, 56) = 15.014, p < .001$. Bonferroni-corrected pairwise contrasts were run to understand this effect. The 45° target was found to have a significantly higher lapse rate than the 0°, 15°, 75°, and 95° targets, smallest $t(14) = 4.15$, largest $p = .010$. No other pairwise comparison was significant, largest $t(14) = 1.95$, smallest $p = .711$. This result suggests that the 45° target was the most difficult to find of all the tested target orientations. On the face of it, the results for the threshold appear to contradict the results for the lapse rate, which suggest that there are only two categories for orientation centred

on 0° and 90° (Foster & Ward, 1991). However, both parameters are a measure of performance and should therefore be correlated. There may be several explanations to explain performance on our task, though none of them is particularly satisfactory.

The first explanation is that certain configurations of distractors could encourage the creation of textures through gestaltian-like grouping, making those displays easier to search (Bergen & Julesz, 1983; Julesz & Bergen, 1983). However, we do not believe that this was the case. If certain combinations of distractors allowed them to be grouped or categorised separately for the target, then we would expect there to be a sudden rise in performance. Given that most data points fit rather closely on their psychometric curves, perceptual grouping or categorical perceptual must not have a large effect. Alternatively, the configurations where grouping occurs may be the ones where the result lies on the lower asymptote of the psychometric curve and thus not affect our results.

Another possible explanation is one that involves vertical symmetry. Vertical symmetry has been known to affect visual search in two ways (Wolfe & Friedman-Hill, 1992). First, when target and distractors are symmetrical, visual search has been shown to be more difficult. In our experiment, search when the target was 15° and 75° involved a condition where a distractor was a mirror of the target. However, the points at which these occur though still fall upon their respective psychometric curves, and as such, any effect of symmetry may have would be small. Second, when the distractors are symmetrical, visual search becomes easier. In our experiment, distractor symmetry occurs only when the target is vertical or horizontal. This explanation can therefore explain why the vertical and horizontal targets have the lowest threshold and lapse rates. However, it cannot explain the differences between the 15°, 45°, and 75° targets.

The final potential explanation is that our search task was subject to the effects of a perceptual phenomenon known as the “oblique effect”. There is converging evidence from psychophysics, neuroscience, and animal studies that sensitivity is greatest to horizontal and vertical orientations and least sensitive to orientations 45° from those (e.g., Appelle, 1972; Blakemore & Cooper, 1970; Maloney & Clifford, 2015). However, this explanation cannot explain why the 45° target had a lower threshold than the 15° and 75° targets.

Given our inability to explain why the lapse rate results differ from the threshold results, we would have to conclude that the lapse rate and threshold are measuring two uncorrelated aspects of visual search. This thus makes it difficult to draw conclusions on the number of categories of orientation that can be used to guide visual search. Before fully considering this line of reasoning, it is important to note a possible confound in the experiment. In order to keep the distance between the items relatively constant between trials, the target and distractors were arranged on a grid-like formation, with a

bit of jitter. This grid-like formation could have created an imaginary vertical and horizontal outline around the search display. It is also possible that the grid-like formation itself provided a strong, objective vertical and horizontal standard for participants to use. Both of these could have made the searches for the horizontal and vertical targets easier than search for the other orientations. Furthermore, as with all unexpected findings, it is important to replicate it to lower the possibility that it is a Type I error. Experiment 2 replicates Experiment 1 but arranges the target and distractors in concentric circles. This removes both the grid-like formation and allows for a circularly windowed display.

Experiment 2

The aim of Experiment 2 was to replicate Experiment 1 without the possible confound that the horizontal and vertical targets were more easily found due to the grid-like formation of the elements in the search display. In Experiment 2, the displays were arranged on three imaginary concentric circles, each rotated randomly every trial (see Fig. 2b for an example display). This made it highly unlikely that the presentation of the distractors represented an objective standard of any orientation, and even less likely for there to be a consistent standard across all the trials. Since the results of Experiment 1 turned out to be symmetrical about the 45° target orientation, in Experiment 2 we will test a 30° target instead of the 75° and 90° targets. If the grid-like arrangement did not affect the results, then we expect to replicate Experiment 1. That is, search should be easiest when the target is vertical, and the lapse rate of the 45° target should be the highest.

Method

Participants 12 participants (nine Female, mean age = 20.7 years, rang: 19–23) took part in this experiment. Participants had normal or corrected-to-normal vision. All participants were naïve as to the purpose of the experiment.

Apparatus and stimuli As shown in Fig. 2b the stimulus consisted of a fixation dot and 24 lines, presented on three imaginary concentric circles with radii of 0.93°, 2.17°, and 3.47° of visual angle. Each circle contained three, eight, and 13 lines, respectively, and was rotated each trial by a randomly determined angle. These values were chosen to keep the average distance between each distractor and, hence, the amount of crowding (Bouma, 1970; Korte, 1923), similar to that in Experiment 1. The display had a maximum diameter of 8° of visual angle. The target line was one of four orientations: 0°, 15°, 30°, or 45°. All other aspects of the experiment were the same as in Experiment 1.

Results and discussion

The results of Experiment 2 are shown in Fig. 4. The mean standard deviations, thresholds and lapse rates are shown in Fig. 4b, c, and d, respectively.

The analyses were conducted in a similar fashion as in Experiment 1. A significant effect of target orientation was found in the threshold, $F(3, 45) = 25.021, p < .001$, lapse rate, $F(3, 45) = 6.719, p = .001$; and in the standard deviation, $F(3, 45) = 7.305, p < .001$. To understand these effects, pairwise contrasts were run on all combinations, and the p values were Bonferroni-corrected for the six comparisons. The threshold for 0° and 45° was found to be significantly different from 15° and 30° , smallest $t(15) = 4.704, p = .002$; however, the difference in threshold between 0° and 45° was not significant, $t(15) = 2.329, p = .026$. The 15° and 30° targets were not significantly different either, $t(15) = .266, p = 1.000$. This is largely in line with Experiment 1, although there is no longer a difference between the 0° and 45° thresholds. This can likely be attributed to the exclusion of the grid, making the vertical target less easy to find, although it may also be attributable to the 45° target curve again containing an outlier where the distractors are 0° and 90° (see the purple square in Fig. 4a). This outlier could be artificially lowering the threshold. Removing the outlier increases the threshold from 34.45 to 36.81. While post hoc and thus of dubious value, this adjusted threshold is significantly lower than the threshold of the vertical target, $t(15) = 3.805, p = .010$. The threshold remains significantly lower than for the 15° and 75° targets, smallest $t(15) = 3.520, p = .019$.

For the standard deviation parameter, 45° was found to be smaller than the other orientations, smallest $t(15) = 3.311, p = .029$. The other orientations did not differ amongst themselves, biggest $t(15) = 2.134, p = .039$. This difference in standard deviation for the 45° target was not found in Experiment 1, but it is difficult to know if this is a true difference in standard deviation, again due to the possibility that the outlier is artificially reducing the standard deviation. Removing that outlier increases the mean standard deviation from 8.39 to 13.49, which is in line with the other orientations. Again, while post hoc and thus of dubious value, the repeated-measures ANOVA with this adjusted standard deviation is not significant, $F(3, 45) = 1.683, p = .184$.

For the lapse rate, 45° was found to be significantly different from 0° and 15° , smallest $t(15) = 3.141, p = .004$; however, the difference in threshold between 45° and 30° was not significant, $t(15) = 2.066, p = .044$; and 30° was not significantly different from vertical or 15° , biggest $t(15) = 2.055, p = .046$, nor was 0° different from 15° , $t(15) = 0.117, p = 1.000$. This is in line with Experiment 1, as 45° was found to have the highest lapse rate. The lapse rate for 30° was found not to be significantly different from any other orientation, suggesting that it likely lies in between. This makes it also likely that 45°

and 135° would be the maxima, in terms of lapse rate, if we had tested all orientations.

Generally speaking, the results of Experiment 2 replicate those of Experiment 1, as the two unexpected findings are still present. The outlying data point when the target was 45° and the distractors were horizontal and vertical is still present. In addition, the inclusion of the 30° target allows us to postulate more about the outlier. In Experiment 1, the only other conditions which contained a vertical or horizontal distractor occurred when that target was 15° and the distractors were either vertical and 30° or -60° and horizontal; or when the target was 75° and the distractors were either 60° and horizontal or vertical and 150° . All four of these conditions had performances which lay on the asymptotes of the psychometric curve. By including the 30° target, we introduced a condition where the distractors were vertical and 60° . Performance here did not lie on the lower asymptote, but the data point was not an outlier. This suggests that an outlier would only occur when both distractors are of cardinal orientations.

The other unexpected finding of Experiment 1, that lapse rate and threshold parameters draw different conclusions despite both being measures of visual search performance, is also present in Experiment 2. Having exhausted the possible explanations earlier, we must turn to the possibility that the two parameters are indeed two measures of performance on uncorrelated abilities. What these abilities would be, however, we can only speculate. With no easy way to identify what these parameters reflect, we are forced to turn to an unconventional, more exploratory method.

Early in the field of personality and intelligence psychology, a problem similar to the one we face was encountered. Many tests of personality and intelligence were developed, all of which were reliably capturing meaningful variance but lacked a way to understand the nature of the variance that was being measured. They solved this problem by introducing the concept of “construct validity” (Cronbach & Meehl, 1955). In short, by using correlational matrices and factor analysis, they were able to understand the nature of the variance being measured by looking at which other scales were related or not related. For example, a scale of crystallised intelligence could be identified as such if it correlated well with tests of vocabulary, correlated less with tests of logical reasoning, and not at all with tests of emotional understanding. Alternatively, it could also be identified as such if a factor analysis places the scale on the same factor as other tests of crystallised intelligence rather than a separate factor. In a similar fashion, we currently have two measures (threshold and lapse rate) but are unsure as to the nature of the variance that is being measured. Following the same logic, we can attempt to understand the nature of the variance by seeing what other tasks relate to the threshold and lapse rate measures.

In order to identify the processes that underlie our threshold and lapse rate parameters, we will create three simple tasks

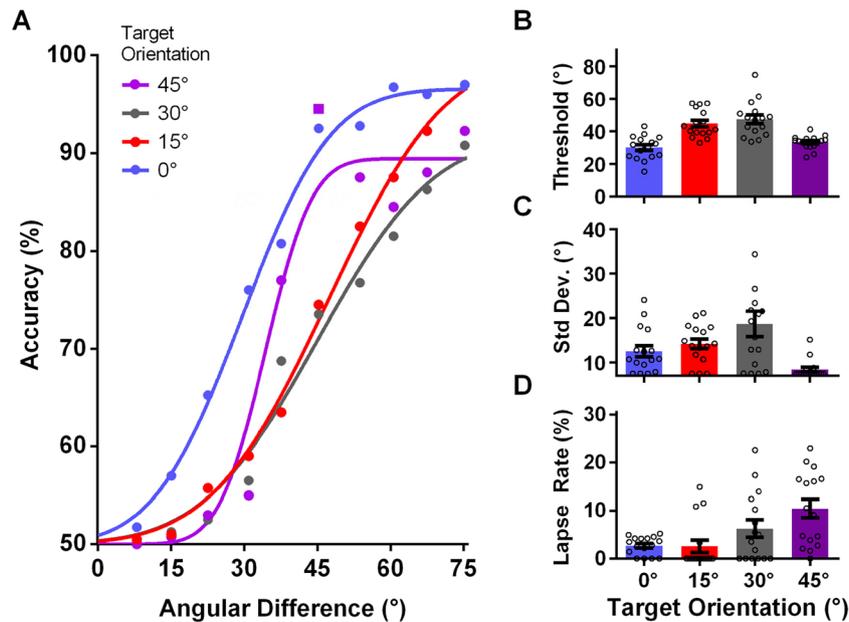


Fig. 4 Results for Experiment 2. **a** Average accuracy across all participants as a function of angular difference (target orientation vs. distractor orientation) for each target orientation. Continuous lines represent the best fitted psychometric curves. **b–d** Average threshold,

standard deviation and lapse rate parameters after fitting each participant's data to a psychometric curve. Error bars represent ± 1 standard error of measurement. (Colour figure online)

that measure each a specific ability: recognition, identification, and reproduction. Recognition is the ability to know that something is a target, as opposed to identification, which is the ability to know what the target is. These two would be classified as perceptual abilities. Reproduction is the ability to accurately recall the target and as such, would be a cognitive ability. Given the relatively large spread of individual thresholds and lapse rates in Experiments 1 and 2 (see Figs. 3b, d and 4b, d), it should be possible to see how performance on the specific tasks relate, and from these relationships understand the variance that our parameters are capturing.

Experiment 3

In Experiment 3, we investigate possible reasons for the dissociation between the threshold and lapse rate measurements in Experiments 1 and 2. To do this, we created three tasks to measure specific abilities: identification and recognition and reproduction. Although not validated, we assume that the identification and recognition tasks measure perceptual resolution, while the reproduction task measures the cognitive ability to create orientations in memory. We then analyse the relationship between performance on these tasks with the threshold and lapse rates obtained for the 45° target, using the same visual search task as in Experiment 2. A correlation in the identification and/or recognition tasks would indicate that the variable is driven by perceptual abilities. A correlation in the reproduction task would indicate that the variable is driven by cognitive abilities.

Method

Participants Forty-eight participants (39 females, mean age = 21.6 years, rang: 19–31) took part in this experiment. Participants had normal or corrected-to-normal vision. All participants were naïve as to the purpose of the experiment.

Apparatus and stimuli Production and presentation of the stimuli were the same as in previous experiments. Stimuli used depended on the task.

Identification task The stimuli consisted of a fixation dot, and four lines (1° in length, 0.2° in width, 100 cd/m²) presented 8° above, below, left, and right of the fixation dot. The orientation of one of these lines was chosen at random to be 45°. The orientations of the other three was determined at random from the possible values of 67.5°, 60°, 52.5°, 37.5°, 30°, or 22.5°, with the restriction that no two orientations could be the same. Participants performed a total of 20 trials. Participants were instructed to press the arrow key corresponding to the location of the line they believed was 45°. Feedback was provided in the form of a green or red fixation dot, for correct and incorrect responses, respectively. Performance was the proportion of trials where the 45° was correctly identified.

Recognition task The stimuli consisted of a fixation dot, and one line (1° in length, 0.2° in width, 100 cd/m²) presented 8° above, below, left or right of the fixation dot, for 500 ms. The orientation of this line was 45° on 15 trials and had an equal

chance of being 55°, 50°, 40°, or -35° on the remaining 15 trials. The order of the trials was randomised. Participants were instructed to press the right arrow key if they believed the presented line was 45° in orientation, or the left arrow key if they did not. Feedback was provided in the form of a green or red fixation dot, for correct and incorrect responses respectively. Performance was the proportion of trials where the 45° line was correctly recognised or the not-45° line was correctly rejected.

Reproduction task The stimuli consisted of a white bar (24° in length, 0.5° in width, 100 cd/m²). The bar was Gaussian blurred across the narrow dimension to remove step-like artefacts that could be used to identify orientation. Before each trial, participants were instructed through text what angle to adjust the bar. On 10 trials, they were instructed to set the bar to 45°, on five trials it was vertical, and on the remaining five trials it was horizontal. The order of the trials was randomised. The initial orientation of the bar was set at a random value between 15° and -15° from the orientation they were to adjust the base to. The bar was adjusted by moving the mouse and pressing the spacebar to confirm. Feedback was not provided for this task.

Performance was calculated as the mean deviation from the target orientation on the 45° trials, minus the mean deviation from the target orientation on the vertical and horizontal trials. The subtraction removes the task-related error.

Visual search task Both the stimuli and procedure for the search task were the same as in Experiment 2, but for the 45° target. Performance was fitted to psychometric curves as in Experiments 1 and 2. The parameters of interest were the threshold and the lapse rate.

Design and procedure All participants performed all tasks in the same session. The visual search task was always performed last, and the order of the other three tasks was counterbalanced across participants.

Results and discussion

Descriptive statistics for the four tasks and the correlations between them are shown in Table 1. Most notably, threshold and lapse rate on the visual search task did not correlate significantly, indicating that performance on these parameters was limited by two different systems. Furthermore, threshold correlated moderately with performance on the reproduction task, and lapse rate correlated moderately with performance on the recognition task.

To investigate this further, we performed a principal components analysis followed by promax rotation. Because there were two factors with an eigenvalue greater than one, and the scree plot indicated a clear break after the second component,

Table 1 Descriptive statistics and Pearson correlations for all tasks used in analyses

	Descriptives			Correlations				
	Mean	SD	N	1	2	3	4	5
1. Identification	0.77	0.15	48					
2. Recognition	0.74	0.13	48	.466**				
3. Reproduction	4.21	2.74	48	-.065	-.113			
4. Threshold	33.16	7.62	48	.197	.017	.291**		
5. Lapse Rate	0.16	0.09	48	-.187	-.351**	.081	-.127	

Note. ** $p < .05$, two-tailed

we chose to adopt a two-component solution, which accounted for 60.9% of the variance. Loadings for the two-component solution are shown in Table 2. An oblique rotation was chosen to allow for possible correlations between the two components, but the correlation between components was negligible ($r = -.02$).

Component 1 was defined most strongly by the identification and recognition tasks, and to a lesser extent by lapse rate. Component 2 was defined most strongly by the reproduction task and the threshold. Given that our two measures in Experiments 1 and 2, threshold and lapse rate, load onto separate components with minimal cross-loadings, it seems that they are indeed measures of two uncorrelated abilities.

The more relevant question for our purposes though is whether threshold or lapse rate measurements is most related to the guidance of attention in visual search. Given the low cross-loadings for each task and the low correlation between the two components, we can use the differences between the identification and recognition tasks on one hand, and the reproduction task on the other, as a proxy measure for the differences between threshold and lapse rate. After all, any similarities between all five measures, such as the fact that they all involve orientation, would be excluded from the PCA as constants. Furthermore, big differences between the tasks that are irrelevant to the difference between threshold and lapse rate would have given rise to a third component.

Given that the reproduction task can be viewed as an untimed, indefinitely looping form of the recognition task, the major difference between the tasks is that an objectively defined 45° line never appears in the reproduction task and the task therefore requires the ability to conjure the 45° orientation into working memory. For the recognition task, this ability would not be needed, as an objective 45° oriented line can be taken from a previous trial. The ability to conjure the comparison orientation into working memory accords well with the idea of a search template in visual search (e.g., Gunseli, Meeter, & Olivers, 2014; Olivers & Eimer, 2011; Vickery, King, & Jiang, 2005), which is consistent with known other effects in visual search where knowledge of the stimulus, and therefore the ease at which a template can be created,

Table 2 Rotated component matrix for the principal components analysis

	Component 1	Component 2
Identification	.753	.126
Recognition	.819	-.109
Reproduction	-.195	.791
Threshold	.229	.809
Lapse rate	-.640	.018

Note. $N = 48$. Component loadings $> |.30|$ are shown in bold

improves performance. The most common example of this is stimulus familiarity (Malinowski & Hübner, 2001; Shen & Reingold, 2001; Wang et al., 1994), however, there is also evidence that the availability of a lexical label for the colour of a target affects search for that colour (Kong, Alais, & Van der Burg, 2016; Yokoi & Uchikawa, 2005). Accordingly, we believe that the threshold measurement aligns more closely to the idea of guidance in visual search rather than the lapse rate.

Although not directly relevant to the immediate question at hand, we believe that the lapse rate would then be a measure of perceptual ability, or the ability to resolve differences in orientation, putting it in line with early, primarily stimulus-based theories of visual search

(Julesz & Bergen, 1983; Treisman & Gelade, 1980). There are several reasons for this belief. First, the lapse rate results accord well with perceptual studies of orientation (i.e., that there is an advantage for vertical and horizontal orientations and a disadvantage for 45° orientations; Appelle, 1972; Blakemore & Cooper, 1970; Mannion, McDonald, & Clifford, 2010). Secondly, although not validated, the identification and recognition tasks can be assumed to share a large perceptual component, and these tasks were grouped with lapse rate to create Component 1 in the PCA.

General discussion

In this study, we investigated visual search for orientation and, in particular, whether there was a category of orientation centred at 45° that can be used to guide attention in visual search. From Experiments 1 and 2 we found two contradictory findings. When looking at threshold measurements, it appeared that there was indeed a channel centred on 45°, although it may not give as big a search advantage as the categories centred on 0° and 90°. However, when looking at lapse rate measurements, it appeared that there was a category centred on 45°, where performance was the lowest of all measured target orientations. This would be indicative of there being only two categories, centred on 0° and 90°, and as 45° was the furthest from either, performance would be worst.

Experiment 3 was conducted to understand why there could be two contradictory findings in the same experiment. Individual variation in lapse rate was associated with the identification and recognition tasks, which required the ability to judge differences between stimuli either presented simultaneously or sequentially. In contrast, variation in threshold was associated with the reproduction task, which required the ability to compare the presented stimulus with a purely internal standard. Therefore, it appears that the findings are due to the threshold and lapse rate measuring two uncorrelated parts of visual search (i.e., stimulus-guided attention and knowledge-guided attention, respectively). We can then conclude that for the purposes of our research question, the threshold measurement is the most relevant and thus there is a category of orientation centred at 45° that can be used to guide attention in visual search, in line with previous work (Wolfe et al., 1992). What is new from this study then, is the apparent weakness of this category compared to the vertical and horizontal categories, indicating that people have more difficulty creating a search template for the category centred on 45°.

The question arises then, of why knowledge of one orientation category is weaker than another. To answer this question, we must first understand the nature of a search template. There is some evidence that a search template is a representation in visual working memory (Olivers & Eimer, 2011; Olivers, Meijer, & Theeuwes, 2006). It is therefore possible that the 45° orientation is being stored with less precision than a vertical or horizontal orientation. However, this seems unlikely, as that would also mean that the width of the category centred on 45° should also be wider. From the standard deviation parameters observed in Experiments 1 and 2, this does not appear to be the case.

The other possibility is that the search template is not being utilised optimally, which could occur, for example, if the cost of creating or maintaining the template is high. The idea that the creation of a search template requires resources has been implicated as the reason why switching costs occur when the target of a visual search task changes (Becker, 2007). Furthermore, the costs of maintaining a search template has been found in EEG studies (Gunseli, Meeter, & Olivers, 2014). This possibility would also explain why it was the lapse rate measurement that was affected by the 45° target (i.e., the lapsed trials were ones where the search template was not available for use). This explanation assumes that creating or maintaining a search template would be harder for one category than another. However, this assumption does not seem unreasonable, given that in the domain of colour, it has been shown that memory for certain colours is better than others (Bae, Olkkonen, Allred, & Flombaum, 2015).

Another question that could be raised in response to our findings is why an attentional system guided by knowledge of the stimulus would follow a different architecture to a system guided by the stimulus itself. We suspect that the answer to

this is that they are using the same architecture, but the input is coming from different ends. Looking at the colour domain, it is known that colour is perceived through three coloured cones in the retina (Svaetichin, 1956) before being processed in LGN with colour-opponent processes (Derrington, Krauskopf, & Lennie, 1984). It is then further processed along the ventral stream (Conway & Tsao, 2006) until the inferior temporal cortex (IT). In IT, cells are then tuned to a limited range of specific colours (Zaidi, Marshall, Thoen, & Conway, 2014). It seems reasonable, then, that the any knowledge of the stimulus would have to use this limited range in IT to feed information back through the visual system. Indeed, there are findings in both the visual working memory (Bae et al., 2015) and visual search (Kong et al., 2016; Yokoi & Uchikawa, 2005) literature that suggest that colour categories are being utilised in their respective tasks.

The final point that will be raised here concerns the outlying data point in both Experiments 1 and 2, when the target was 45° and the distractors were vertical and horizontal. There are two possibilities that might explain this outlying point. The first is that it is fundamentally a different type of search. Given that vertical and horizontal orientations are easier to perceive, it is possible that search for a target amongst horizontal and vertical distractors is a search for what is not a distractor, whereas every other display configuration in our experiment was a search for a target. While there is no theoretical support for this, this theory would be supported empirically if there were little difference in search performance when the target orientation varied, and the distractors were kept constant at vertical and horizontal (i.e., the target/distractor similarity increased).

The other possibility is that the perceptual space is nonlinear (Vighneshvel & Arun, 2013) and thus objective differences in orientation may not correspond with similar differences in performance. For example, Vighneshvel and Arun found that search for a 0° target amongst 20° distractors was easier than a -20° target amongst -40° distractors, despite both searches involving a 20° difference. We do not believe this is the case in our study, however. With the exception of the single outlying point for targets at 45° and distractors at vertical and horizontal, all points lay on their respective psychometric curves and the fits of the curves to the data points were very high (smallest individual $r^2 = .923$). The standard deviation parameter therefore indicates that after stripping away the effect of target orientation, performance had a linear relationship with target-distractor difference. Thus, any nonlinearity could be explained by the target orientation, which as both the lapse rates in Experiments 1 and 2 and the results of Foster and Ward (1991) show, is at least monotonic from 0° to 45°, if not linear. Indeed, all of the irregular display configurations presented in Vighneshvel and Arun's study involved a vertical target orientation, or the target being the only item in the vertical category.

In conclusion, this study systematically investigated the categorical nature of attentional guidance in visual search by systematically varying the target and distractor orientations. Unexpectedly, we found that there were two, independent measures of performance (i.e., the lapse rate, or the maximum performance given the target orientation; and the threshold, or the amount of target/distractor difference required for performance to reach halfway between minimum and maximum performance). We then identified that threshold was most related to the creation and maintenance of a search template through which attention can be guided in visual search. This allowed us to conclude that there are four categories in visual search that can be used to guide attention, centred on 0°, 45°, 90°, and 135°. However, the categories centred on 45° and 135° are weaker than the ones centred on 0° and 90°, and we speculate that this due to the creation and/or maintenance of the 45° and 135° categories being more difficult than the other two.

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