Simple shapes guide visual attention based on their global outline or global orientation contingent on search goals

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Abstract

It is still unclear which features of a 2D shape (e.g., triangle, square) can efficiently guide visual attention. Possible guiding features are edge orientations (single oriented shape edges; e.g., verticals during search for squares), global outlines (combination of the target edges; e.g., squares), or global orientations (specific orientations of global outlines; e.g., squares but not diamonds). Using a contingent-capture protocol, we found evidence for task-dependent guidance by the global shape outline and the global shape orientation. First, if participants searched for a shape (an equilateral triangle) independent of its pointing direction, cues with the same global shape outline as the target captured attention, even without sharing any edge orientations with the target. Secondly, however, if a shape's specific pointing direction was task-relevant, attentional guidance changed to the specific orientation of the global shape. Our results show that the global shape outline and the global shape orientation can both guide visual attention, contingent on the nature of the shape and the current search goals. We discuss differences between shapes (equilateral triangles and isosceles trapezoids) considering models of shape perception and conclude with a critical review of the contingent-capture protocol as a complementary method to visual search protocols.

Keywords: visual attention, shapes, contingent capture of attention, top-down attention, orientation, attentional control settings

Public Significance Statement:

This study shows that when we search for a 2D object, its shape can be used to guide our visual attention so that we can efficiently find the object. In contrast, oriented edges of such a 2D object are not sufficient to explain successful search for shapes. Whether the orientation of a shape is also used to guide attention depends on the shape itself and on the necessities imposed by the search context.

Simple shapes guide visual attention based on their global outline or global orientation contingent on search goals

At each moment, humans process only a limited amount of the available visual information (e.g., Helmholtz, 1894). The selection of relevant stimuli for further processing is referred to as visual attention (cf. Carrasco, 2011; Moore & Zirnsak, 2017). Visual attention is influenced by stimulus properties (e.g., salience, target-distractor relationship) and individual top-down and memory factors like searching for a specific color or voluntarily orienting attention towards a specific location (Awh et al., 2012; Jonides, 1981; Wolfe & Horowitz, 2017). Some visual features can guide attention more efficiently than other features. For example, searching for a specific color, motion, orientation, or size is often effortless if feature differences between target and distractor are huge (Wolfe & Horowitz, 2004, 2017). However, if 2D shapes can guide attention effectively is not yet clear (cf. Dickinson, Bell, & Badock, 2013; Dickinson, Haley, et al., 2018; Donnelly et al., 2000; Green et al., 2018; Wolfe & Bennett, 1997). Therefore, Wolfe and Horowitz (2017) list shape only as a probable guiding feature, mainly because there is evidence that shape can guide attention (cf. Alexander et al., 2014; Enns & Rensink, 1990; Pomerantz & Pristach, 1989), but it is unclear which features of shape can guide visual attention efficiently. Shape features can be divided into local and global features. Local features are derived from only a part of the shape. Examples are the orientation, concavity, or convexity of single edges of a shape and points of maximum curvature (e.g., corners). Global features arise from the whole shape. For example, the summary statistic of a shape, the global shape outline (i.e., the combination of single edges that constitute the shape), or the global shape orientation (e.g., the rotation or pointing direction of the shape regarding a frame of reference).

For example, Wolfe and Bennet (1997) found that it is difficult to search for a target shape amongst distractors consisting of the same but reconfigured line segments as the target shape. They concluded that the global shape outline is not effective in guiding attention. However, Donnelly et al. (2000) showed that such a search task (where target and distractors are constructed from the same oriented line segments) could be easy if the distractors are homogenous. The search task is only difficult if the distractors are heterogeneous. In the current study, we used improved methodology (see below) to test if global shape outlines and global shape orientation can efficiently guide attention during search for 2D objects. In Experiment 1, we tested if our method is suitable to answer our research questions. In Experiment 2 and 3, we tested whether the global shape outline can guide visual attention while controlling for guidance by single shape edges. In Experiments 4 to 7, we tested whether global shape orientation can be an attentional guiding feature and if the global shape orientation or global shape outline can be flexibly used as a guiding feature dependent on the search task.

Measuring Attentional Guidance with Visual Search Tasks

Typically, attention guidance is measured using visual search tasks (e.g., Donnelly et al., 2000; Duncan & Humphreys, 1989; Egeth & Dagenbach, 1991; Enns & Rensink, 1990; Pomerantz & Pristach, 1989; Treisman & Gormican, 1988). In such experiments, participants search for a predefined target. Then, in each trial, a target is presented (or sometimes not presented) unpredictably at one of several potential positions. The target is presented among irrelevant distractors (e.g., stimuli with different features than the target), while, between conditions, the number of distractors (i.e., the set size) varies.

Visual search's efficiency is determined by search times divided by the number of distractors (i.e., the set-size effect). For example, if the average time to find the target among two distractors is 500 ms, but among ten distractors 660 ms, one would assume that each distractor captured and kept participants' attention for about 20 ms (cf. Treisman & Gelade, 1980; Wolfe, 1994). If each distractor increases search time by more than 10 to 20 ms, attentional guidance is considered slow and inefficient, while no or only a small increase in search time characterizes efficient attentional guidance.

However, this rationale is questionable for several reasons. First, search times typically reflect a combination of overt shifts of the eyes, covert attentional allocation, and dwell times (Findlay & Gilchrist, 1998; Hulleman & Olivers, 2017; Pomplun et al., 2003; Trukenbrod & Engbert, 2014). If eye movements increase with set size, search times may increase for higher numbers of stimuli due to saccadic suppression rather than guidance alone (Vaughan & Graefe, 1977). Secondly, a much higher number of distractors than targets can invite strategies of suppressing or rejecting the distractors (cf. Chetverikov et al., 2020; Duncan & Humphreys, 1989; Lamy et al., 2013; Rauschenberger & Yantis, 2006; Snyder & Foxe, 2010; Utochkin, 2013). As interesting as these strategies might be, they are not reflective of the template used to search for target shape. Thirdly, the time for revisiting already inspected distractors inflates search times. Thus, imperfect memory for already scanned locations compounds the interpretation of search times as evidence for attention capture and dwelling of attention (Findlay & Gilchrist, 1998; Husain et al., 2001). Therefore, we suggest complementing the established interpretation of search times as a function of set size by using contingent-capture protocols (cf. Folk et al., 1992).

Measuring Attentional Guidance with Spatial Cuing

In the contingent-capture protocol, insights into the attentional control settings are gained using a cueing display, which precedes the target display (Folk & Remington, 1998; Folk et al., 1992). As in visual search, participants search for a target presented at one of several possible locations. The cues are presented either at target position (valid condition) or away from the target (invalid condition), and cues are not spatially predictive of the target position. In this situation, allocation of attention to the cues results in a validity or cueing effect: target search is facilitated (i.e., faster reaction times) in valid relative to invalid conditions. Validity effects are usually only found for cues that are sufficiently similar to the searched-for target feature (Folk & Remington, 1998; Folk et al., 1992; for a review see Büsel et al., 2020). Therefore, researchers consider validity effects often as evidence for top-down contingent capture, meaning that cues capture attention contingent on the match between attentional control settings and cue features (Folk et al., 1992). Validity effects of cues with varying target similarity, thus, provide insight into attentional control settings established during target search. In comparison to search times, contingent-capture effects have several advantages: Attention capture by and dwelling of attention at target-similar cues via validity effects is not (or at least less) prone to (1) different degrees of overt eye movements between conditions, (2) strategies for the suppression of distractors, and (3) memory failure for already scanned positions. Therefore, using a contingent-capture protocol might help to solve contradicting conclusions from visual search experiments.

Here, we used a contingent-capture protocol to, first, investigate whether the global shape outline can efficiently guide visual attention if no single shape edge matched any target shape edge, and second, whether the global shape orientation can guide visual attention efficiently as well. In visual search tasks, when the distractors are homogenous, the global shape orientation can be seemingly searched for efficiently (cf. Enns & Rensink, 1991; Found & Müller, 1997). However, as explained, the dependence on homogenous distractors might indicate that (1) distractor suppression plays a role and (2) that attention is guided by a more basic feature such as the orientation of single shape edges, and search would, thus, be disrupted by more edge-heterogeneous distractors (cf. Wolfe & Horowitz, 2004).

So far, contingent capture by specific shapes or their orientation has rarely been addressed. Biderman et al. (2017) found attentional capture selectively by relevant shape cues. Adamo et al. (2010) showed parallel attentional control settings for shape and location. Finally, Berggren and Eimer (2018) found neurophysiological evidence for target-specific attentional capture (see also, McCants et al., 2018). However, in all these studies, edge orientations of the matching cue and the target were at least partly the same, leaving it open if participants can efficiently search for a global shape outline consisting of a combination of oriented edges.

Throughout all experiments, our participants searched for a target shape among three different shape distractors. Thus, top-down singleton search was not feasible (cf. Bacon &

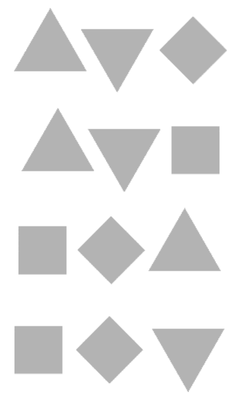
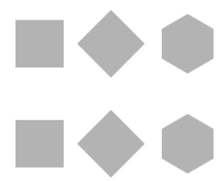
Egeth, 1994). The cueing display always consisted of one spatially non-predictive shape cue presented among three disks. Thus, the cue was always a shape singleton and, therefore, salient (cf. Itti et al., 1998; Li, 2002; Nothdurft, 1993; van Zoest & Donk, 2004; but see Theeuwes, 1992, for evidence to the contrary in case of shape singletons). We used a variety of cues to test whether the global shape outline (Experiments 1–3) or the global shape orientation (Experiments 4–7) can guide visual attention and whether guidance of those shape features is search-goal dependent.

Experiment 1

In Experiment 1, we tested whether the contingent-capture protocol is suited to measure attentional capture by shapes during search for a simple 2D target shape. Participants searched for one specific shape (a triangle pointing up, a triangle pointing down, a square, or a diamond, randomly assigned to each participant), and we used two types of cues: cues that were of the exact same shape as the target (matching cues), and cues that were of a different shape than the target (non-matching cues). The matching cues shared all possible shape features (e.g., global shape outline, global shape orientation, and single shape edges) with the target. Thus, whatever the actual guiding feature is, if contingent-capture protocols are suited for the study of attentional control settings for shape, we expected to find more attention capture (i.e., stronger validity effects) of the matching cues than of the non-matching cues. Table 1 provides an overview of the shapes used as the target, cue, and distractors in Experiments 1 to 3.

Table 1

Shapes Used in the Cueing and Target Displays of Experiments 1 to 3

Target Shape (= Matching Cue)		Other Cue Types		Distractors
Experiment 1		non-matching		
	42 ms **		−1 ms	
Experiment 2		reconfigured matching edges		
	40 ms **		59 ms **	
Experiment 3		reconfigured matching edges		
	62 ms **		64 ms **	
	49 ms **		57 ms **	
		non-matching edges		
	32 ms *		−8 ms	
	13 ms *		11 ms	

Note. Each participant searched for only one 2D target shape. The non-matching cue share no feature with the target shape. All other cues shared the global shape outline with the target. Next to the cue shapes is the validity effect and *p* value for the *t* test against zero.

* $p < .05$. ** $p < .001$.

Method

Participants

In all experiments, we decided in advance for a sample size between 20 and 25 participants. We tested at least 20 participants but did not send away already registered participants if the sample size was still lower than 25. According to classical power analysis (e.g., with G*Power, Faul et al., 2009), a sample of 20 participants results in a power of .97 to find an effect of Cohen's *d* = 0.9 (for a two-sided one-sample *t* test with a significance level of .05). The effect size of 0.9 is about half of the mean effect size of contingent-capture experiments reported in a recent meta-analysis (Büsel et al., 2020).

In Experiment 1, we analyzed data from 22 participants (18 women, 4 men) aged between 19 and 24 years (*M* = 20.14, *SD* = 1.61, *Mdn* = 19.50). An additional seven participants could not finish the 20 practice trials with less than 20% errors after five attempts and, therefore, were excluded before data collection started. Three participants with more than 45% errors (chance level was 50%) were excluded after data collection. With 22 participants, this experiment achieved a simulated power of .81 to find a validity effect of 20 ms. Details about the measurement precision and the simulation used for estimating the achieved power in this and all following experiments are presented in the Appendix.

Here and in the following experiments, all participants had self-reported corrected or corrected to normal visual acuity, no red-green deficiency (examined with Ishihara color plates) and gave written informed consent before the experiment. In all experiments, participants received course credits for their participation and were treated in compliance with the ethical standards of the Declaration of Helsinki as well as the national and institutional ethical standards.

Design and Procedure

The design consisted of two independent variables, cue type (matching vs. non-matching) and validity (valid vs. invalid). The matching cue was the same shape as the target shape, whereas the non-matching cue was always a hexagon.[1] A condition was valid if the target appeared at the same location as the cue, and invalid if it appeared at a different location.

The participants sat in a dimly lit room in front of an LCD monitor with a resolution of 1,280 x 1,024 pixels (37.7 x 30.2 cm) and a refresh rate of 60 Hz. A chin rest assured a viewing distance of 57 cm to the center of the monitor. We used MATLAB (The Mathwork, Inc., Natick, Massachusetts, USA) version 7.7 (R2008b) and the Psychtoolbox 3.0.8 (Brainard, 1997) to program and control the experiment.

Before data collection, participants had to complete 20 practice trials with more than 80% correct answers. Targets could appear at four locations (see Figure 1) and positions of

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[1] As the hexagon was used as a non-matching cue, in a control experiment, we made sure that the hexagon is salient enough to capture attention, too. If used as the target shape, we found a validity effect of the hexagon cue significantly higher than zero, M = 26 ms, 95% CI [10, 41], SD = 22 ms, $t(9) = 3.70$, $p = .005$, $d_{unb} = 1.07$ [0.33, 1.97]. This result indicates that a hexagon amongst circles would be salient enough to selectively capture attention.

cues and targets were uncorrelated across trials. The experiment consisted of 576 trials (72 [25%] valid and 216 [75%] invalid trials for each cue type), with one break after half of the trials. The whole experiment lasted about 30 min.

In each target display, participants saw four different shapes (square, diamond, triangle pointing upwards, and triangle pointing downwards), each with a small red or green disk at its centroid. The task was to report the color of the disk (red or green) inside the target shape via pressing the *J* or *F* key on a keyboard. The mapping of *J* and *F* to the colors was balanced across participants. Always two of the disks were red, the other two green, and all six possible distributions of colors across locations occurred equally often.

The target shape was fixed throughout the experiment but counter-balanced and randomly assigned to the participants, resulting in five to six participants per target shape. However, we analyzed data collapsed across all target shapes, as analyses for each target shape were not planned for and, hence, results for different target shapes would be based on small sample sizes.

Each trial started with a 750 ms lasting fixation display, in which only a small black dot was presented at the screen center. Next, the cue display appeared for 50 ms, consisting of four shapes. One singleton shape was the cue, either matching (same shape as the target shape; 50% of trials) or non-matching (hexagon; other 50% of all trials), while the other three shapes were always disks. Next, a masking display was shown for 100 ms consisting of four disks. The masking disks covered the shapes in the cue display, thus, eliminating possible perceptual facilitation by the repetition of the same shape at the same location in the target display. Immediately after the masking display, the target display was shown for 350 ms.

After the target display, only a black dot at screen center was shown for 1 s or until response. If participants did not respond within 1 s, the sentence "Zu langsam, bitte schneller reagieren. [Too slow, please react faster.]" was shown for 1 s. If a response occurred, the fixation display of the next trial started after 500 ms. See Figure 1 for an illustration of the sequence of displays in a trial. The order of the trials was pseudo-randomized, with each type of stimulus appearing equally often at each location.

Stimuli

The stimuli were presented at the corners of an imaginary square at the center of the screen. The horizontal and vertical offset from the center was 6.38° of visual angle. The background of the display was grey (CIELAB color space: L* = 70, a* = 0, b* = 0), and all shapes were white (L* = 120, a* = 0, b* = 0). At the centroid of each shape was a red (L* = 70, a* = 94, b* = 92) or green (L* = 70, a* = −79, b* = 51) disk with a diameter of 0.89°.

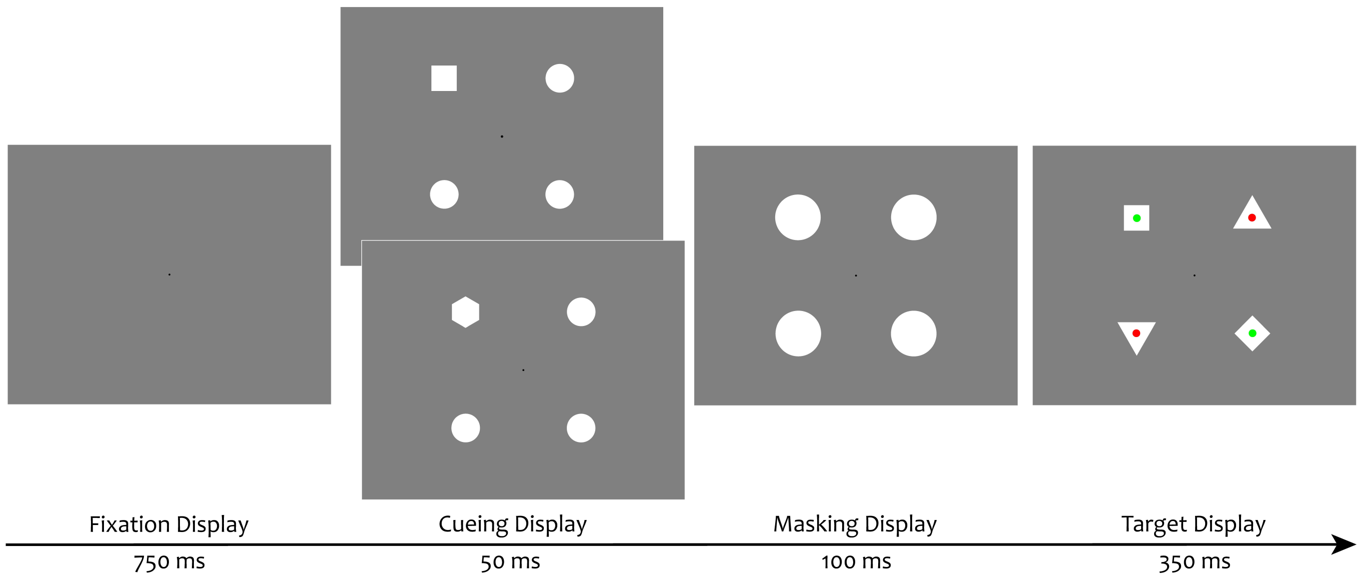
Each shape had the same area, except the masking shapes (disks of 5.04° diameter). The square and diamond had a side length of 2.85°, the equilateral triangles of 4.33°, and the hexagon of 1.77°. The non-singleton disks in the cueing display had a diameter of 3.22°.

Data Analysis

For our analyses, we used R (Version 3.6.3; R Core Team, 2019) and the R-packages *data.table* (Version 1.12.8; Dowle & Srinivasan, 2019), *emmeans* (Version 1.4.6; Lenth, 2019),

Figure 1

Procedure of Experiments 1



Note. Depicted are valid trials, with a matching cue (upper cueing display) and non-matching cue (lower cueing display). All stimuli are drawn to scale.

ggplot2 (Version 3.3.0; Wickham, 2016), *lme4* (Version 1.1.23; Bates et al., 2015), *outliers* (Version 0.14; Komsta, 2011), *psychometric* (Version 2.2; Fletcher, 2010), and MBESS (Version 4.4.3, Kelley, 2020). We analyzed only correct reaction times between 150 ms and 1 s. Our measure for attentional capture was the validity effect – that is, the reaction time difference between invalid and valid trials. A positive validity effect can be interpreted as attentional capture by (and attentional dwelling at the position of the) cue. The validity effect was calculated for each participant separately, resulting in one value per participant and condition. We used one-sample *t* tests to find out whether the validity effect elicited by different cue types was significantly different from zero (for all analyses, we used a significance level of $\alpha = .05$), and a one-sample *t* test of the per-participant differences between cue types to test if there is a significant difference between the cue types. If more than one comparison was made, we adjusted the *p* values using the procedure of Benjamini and Yekutieli (2001).

Additionally, we analyzed the error rates using a generalized linear mixed-effect model with a binomial link function (here: a logistic cumulative density function). This approach is recommended over an analysis of variance (ANOVA) with arcsine transformed error rates (e.g., Jaeger, 2008). Error rates analyses and mean reaction times of all experiments are reported in the Supplemental Materials.

Results

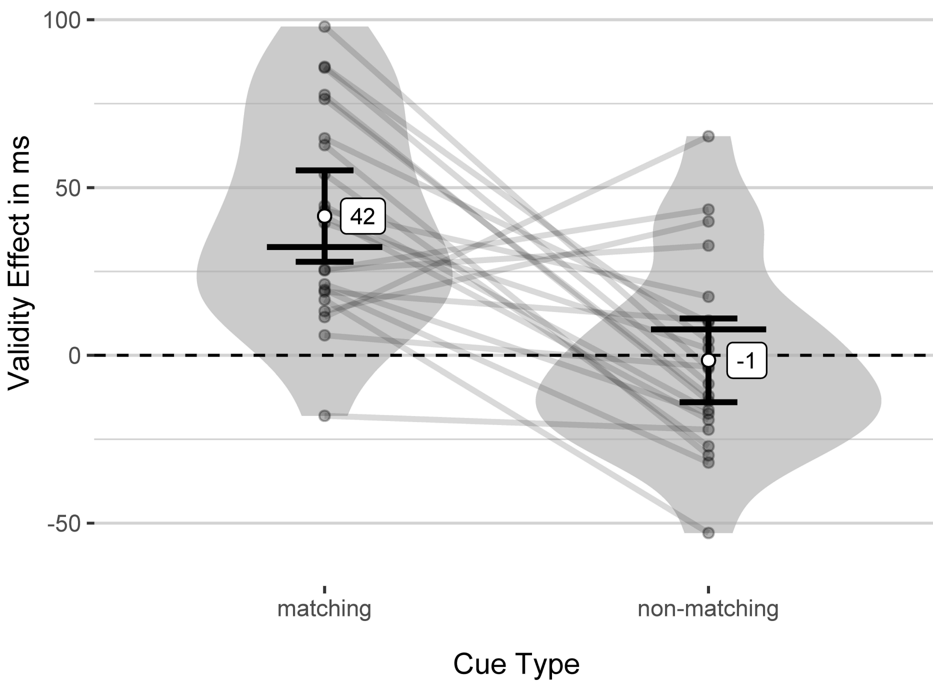
For the validity-effect analysis, we excluded 3.01% reaction times below 150 ms and above 1 s and 15.50% of the remaining trials with wrong answers. After the exclusions, the number of valid matching trials ranged from 46 to 70 (M = 60.32, SD = 5.92, Mdn = 61.50) per participant, and of valid non-matching trials from 49 to 70 (M = 60.55, SD = 6.65, Mdn = 62.50). Invalid trials occurred about three times as often and, thus, measurement precision is always at least as good as in the valid conditions.

Validity Effect

A Shapiro-Wilk test showed that the validity effects did not significantly deviate from the normal distribution (W = 0.96, p = .51, for matching cues and W = 0.96, p = .50, for non-matching cues). Using a two-sided one sample *t* test against zero, we found a statistically significant validity effect for matching cues, M = 42 ms, SD = 31 ms, 95% CI [28, 55], $t(21) = 6.33$, $p < .001$. This effect constitutes a standardized effect size of d_{unb} = 1.30 [0.76,

Figure 2

Validity Effects (Invalid Minus Valid Reaction Times) in Experiment 1



Note. The narrow error bars represent the 95% CI for the one-sample *t* test against zero (dashed line). The wide error bars represent the 95% CI for the difference between the validity effects. The lowest and highest values have only one error bar since only one comparison is possible. Non-overlapping error bars indicate a significant difference.[2]

1.92], where d_{unb} ($_{unb}$ stands for unbiased) is the effect relative to the standard deviation adjusted using the correction factor described by Hedges (1981). This adjustment is necessary since *d* is biased and overestimates the population effect sizes, especially if the

[2] CIs are generally not suitable for comparisons since they can be misleading. However, we used the comparison arrows from the R package *emmeans* to plot the CIs, which are designed to show a significant difference adjusted for multiple comparisons (if applicable).

sample size is below 50 (cf. Cumming, 2012). The 95% CI is calculated around the biased *d*, since it is the better estimator for the CI (Cumming, 2012, p. 307). The validity effect for non-matching cues was non-significant, $M = -1$ ms, 95% CI [−14, 11], $SD = 28$ ms, $t(21) = -0.25$, $p = .81$, $d_{unb} = -0.05$, [−0.47, 0.37]. The validity effect difference between matching and non-matching cues was also normally distributed ($W = 0.94$, $p = 0.19$) and significant, $M = 43$ ms, 95% CI [23, 63], $SD = 45$ ms, $t(21) = 4.51$, $p < .001$, $d_{unb} = 1.41$, [0.85, 2.06]. Figure 2 shows the validity effects.

Discussion

In Experiment 1, we found a validity effect for matching cues only, indicating that the contingent-capture protocol can be used to study the nature of how search goals guide visual attention toward shapes of different degrees of target similarity. The absence of any validity effect of non-matching cues shows that these cues were ignored within the 150 ms since cue onset or even before attention was allocated to their locations. This might be due to an attentional control setting for shapes (cf. Berggren & Eimer, 2018; Biderman et al., 2017; Nako et al., 2014; Pomerantz & Pristach, 1989). However, the matching cue had the same shape as the target and consisted of the same edges. Therefore, the guiding feature(s) might have been all, some, or one of the target-matching edges of the shape instead of the global shape outline (cf. McCants et al., 2018). To test whether attentional guidance during search for shapes in general and in Experiment 1, in particular, was based on exactly matching edges, we used a cue shape with reconfigured edges in Experiment 2.

Experiment 2

In Experiment 2, the target shape (and matching cue) was an equilateral triangle. A 180°-rotated version of the target served as a cue with the same global shape outline but differently configured edges. The 180°-rotated cue consisted of the same three edge orientations as the target (one horizontal edge, one tilted to the left, and one tilted to the right) but spatially combined in a different way. Therefore, we refer to this as a “reconfigured matching cue” (i.e., a shape with reconfigured but matching edges).

If attentional guidance is based on edges matching the same orientation and spatial position as the target, the cue with reconfigured matching edges should not capture attention. However, if the global shape outline or the target-matching edges guide visual attention independently of their spatial configuration, this cue would capture attention as well.

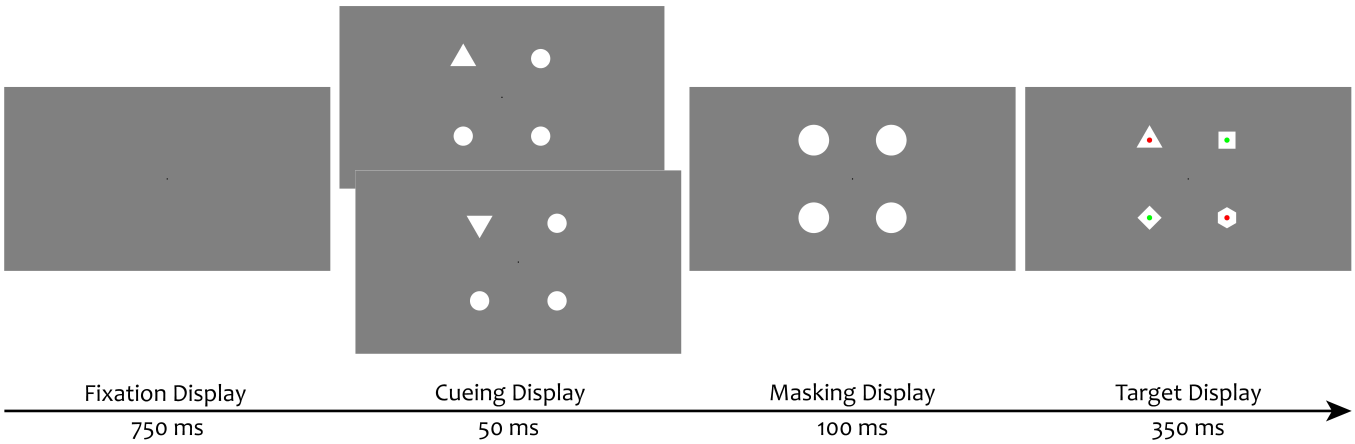
Method

Participants

In Experiment 2, we analyzed data from 21 participants (11 women, 10 men) aged between 18 and 31 years (M = 22.05, SD = 3.23, Mdn = 21). All participants were able to finish the 20 practice trials with less than 20% errors after a maximum of three attempts. We excluded the data of one participant with 40.97% errors (an outlier according to a one-sided Grubbs test, p = .01). With 21 participants, this experiment achieved a power of .95 to find a validity effect of 20 ms. The higher power compared to Experiment 1 was achieved by increasing the number of trials per experimental condition.

Figure 3

Procedure of Experiment 2



Note. Depicted are valid trials for the triangle pointing upwards as target shape. The upper cueing display depicts a trial with a matching cue and the lower cueing display a reconfigured cue (with reconfigured matching edges; 180°-rotated version of the target shape). All stimuli are drawn to scale.

Design and Procedure

Except for the following changes, the design and procedure were the same as in Experiment 1. Each participant searched consistently for an equilateral triangle pointing upwards or downwards (randomized between participants). The matching cue had the same shape and orientation as the target, while the other cue was 180° rotated. The rotated triangle was not present in the target display and was replaced by a hexagon (see Figure 3). The experiment consisted of 1,152 trials (144 valid and 432 invalid trials per each cue type) and lasted about 45 min.

Stimuli

The data was collected on a different LCD monitor (AOC Gaming Monitor G2590PX, 24.5 in) than in Experiment 1. The resolution was 1,920 x 1,080 pixels (54.4 x 30.3 cm) and the refresh rate 100 Hz. Nevertheless, the sizes and positions of all stimuli were the same as in Experiment 1 relative to the center of the screen. MATLAB was updated to Version 9.6 and the Psychtoolbox to Version 3.0.15. The colors changed slightly. White was now defined as L* = 140, a* = 0, b* = 0, red as L* = 70, a* = 99, b* = 90, and green as L* = 70, a* = −70, b* = 67.

Results

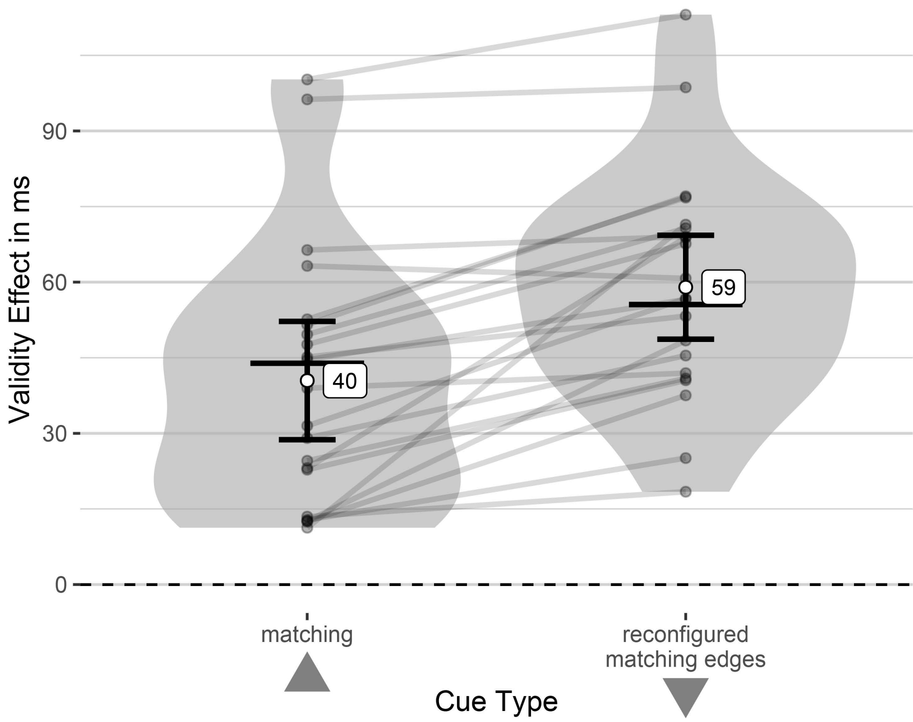
For the validity-effect analysis, we excluded 1.46% of all trials with reaction times below 150 ms and above 1 s and 11.74% of the remaining trials with wrong answers. These exclusions left us with 107 to 142 valid matching trials per participant (M = 129.62, SD = 9.86, Mdn = 131), and 112 to 140 (M = 129.10, SD = 8.47, Mdn = 130) valid trials with reconfigured matching cues.

Validity Effect

Since a linear mixed-effect model with the fixed factors cue type (matching vs. reconfigured; within participant) and target pointing direction (triangle pointing up vs. pointing down; between participants) and a random per-participant intercept showed no significant interaction between cue type and target pointing direction (p = .28) and no significant main effect of target pointing direction (p = .92), we collapsed data across both target conditions.

Figure 4

Validity Effects (Invalid Minus Valid Reaction Times) in Experiment 2



Note. The error bars represent the 95% CI for the one-sample *t* test against zero (dashed line). The wide error bars represent the 95% CI for the difference between the validity effects. The lowest and highest values have only one error bar since only one comparison is possible. Non-overlapping error bars indicate a significant difference.

A Shapiro-Wilk test for normality showed that the validity effect for matching cues did significantly deviate from the normal distribution (W = 0.90, p = .03). However, since other tests for normality did not show a significant deviation (Anderson-Darling test, p = .09, Cramér-von Mises test, p = .22) and a Wilcoxon signed-rank test yielded the same result as a *t* test, we decided to use the latter for consistency. For the reconfigured matching cues, the validity effect was normally distributed, W = 0.97, p = .71.

The validity effect for matching cues (M = 40 ms, 95% CI [29, 52], SD = 26 ms) was significantly higher than zero, $t(20) = 7.19$, $p < .001$, $d_{unb} = 1.51$, [0.92, 2.21]. Likewise, the validity effect for reconfigured matching cues (M = 59 ms, [49, 69], SD = 23 ms) was significantly higher than zero, $t(20) = 11.93$, $p < .001$, $d_{unb} = 2.51$, [1.69, 3.50]. The difference between both cue types was also normally distributed ($W = 0.91$, $p = 0.07$). The validity effect of matching cues was significantly lower compared to reconfigured matching cues, M = −19 ms, 95% CI [−25, −12], SD = 15 ms, $t(20) = -5.62$, $p < .001$, $d_{unb} = -0.74$, [−1.25, −0.27]. Figure 4 shows the validity effects.

Discussion

In Experiment 2, we tested whether the contingent attentional capture of target-matching cues in Experiment 1 occurred due to the cues' target-matching edges. Line orientation can guide visual attention in a top-down manner (e.g., Cavanagh et al., 1990; Treisman & Gormican, 1988; Wolfe et al., 1992; but see also Du & Abrams, 2012). Therefore, target-matching edges might have captured attention instead of the global shape outline. To control for this possibility, we used a 180°-rotated cue. This cue shared the global shape outline with the target, but its edges were spatially reconfigured. Therefore, no cue edge matched any target edge at the same relative position within the shape. However, the reconfigured matching cue consisted of the same three edge segments (horizontal edge, left and right tilted edge) as the target.

We found that the reconfigured matching cue elicited a significant validity effect at least as strong as that of the matching cue.[3] It seems that the attentional control settings established during the search for an equilateral triangle is not specific for edges matching the orientation and their relative spatial positions to the target shape. This result indicates that attentional control settings might be sensitive to the global shape outline (which is preserved in the reconfigured/180°-rotated cue). However, it is also possible that these settings are sensitive to target edges without a specific spatial arrangement (cf. Wolfe & Bennet, 1997). Therefore, we conducted Experiment 3 to find out whether the global shape outline or spatially rearranged target edges guide visual attention.

In Experiment 3, we used squares instead of equilateral triangles as the target shape. Here, a 45°-rotated version of a square (i.e., a diamond shape) consists of entirely different edge orientations than a square, as it uses oblique edges instead of horizontal and vertical edges. However, the global shape outline is geometrically the same. Despite sharing the same global shape, squares and diamonds are perceived as qualitatively distinct (Clément & Bukley, 2008; Mach, 1922; Rock, 1974). Therefore, using squares and diamonds as stimuli allowed us to investigate how differently perceived, but geometrically identical shapes guide

[3] Puzzling to us, the validity effect of reconfigured cues was even stronger than for matching cues. Using the same triangle targets, this difference did not replicate in Experiment 3, but we observed it again in Experiment 4.

visual attention. Furthermore, we also kept equilateral triangles as target shapes to replicate Experiment 2.

Experiment 3

Each participant searched for one equilateral triangle (pointing upwards or downwards, randomly assigned to each participant) in the first block and a square or diamond (also randomly assigned) in the second block, or vice versa. In each target condition, we used two types of cues: matching cues with the exact same shape as the target and rotated cues with the same global shape outline. These cues were 180°-rotated during the search for triangles, resulting in cues with target-matching but reconfigured matching edges (as in Experiment 2) and 45°-rotated during the search for squares or diamonds, resulting in cues with non-matching edges but preserved geometric global shape outline. In the square and diamond target conditions, the cue with the non-matching edges should only capture attention if the global shape outline guides visual attention. Attentional guidance by target-matching but spatially rearranged edges should not be sensitive to rotated square or diamond cues, as they share no edge orientations with the target shape (only oblique edges [cue] vs. vertical and horizontal edges [target], or vice versa).

Method

Participants

In Experiment 3, we analyzed data from 30 participants (16 women, 14 men) aged between 19 and 35 years (M = 22.57, SD = 3.33, Mdn = 22). Three participants were excluded before the data collection started because they did not finish the practice trials with less than 20% errors after more than three attempts. No participant was excluded after data collection.

We increased the sample size to 30 participants per target condition (equilateral triangles and square or diamond), since we wanted to replicate Experiment 2 with higher statistical power. Half of all participants searched for one oriented triangle target (either upwards or downwards pointing, between participants) in one block and for one oriented quadrangle target (either square or diamond, between participants) in the other block. Which triangular target variant was paired with which quadrangular target variant and which of these two target search conditions came first was balanced across participants. However, we had to analyze each target condition variant separately (see Results). Therefore, the sample size for each target condition variant was smaller than desirable (16 participants in the diamond condition, 15 in the triangle pointing up condition, and 14 participants for the square and triangle pointing down condition). With 14 participants, this experiment achieved a power of .70 to find a validity effect of 20 ms (the power was higher in the conditions with more participants).

Design and Procedure

Design and procedure were the same as in Experiment 2 with the following exceptions. In the equilateral triangle target block, the hexagon distractor was replaced with an octagon. In the square or diamond target block, the distractors were an octagon, a triangle pointing upwards, and a triangle pointing downwards (see Table 1). Following practice, the experiment consisted of 1,152 trials (144 valid and 432 invalid trials for each cue type) and lasted about 45 min.

Stimuli

The hardware and the stimuli were the same as in Experiment 2. The (previously not used) octagon had a side length of 1.27° resulting in the same area as the other used stimuli.

Results

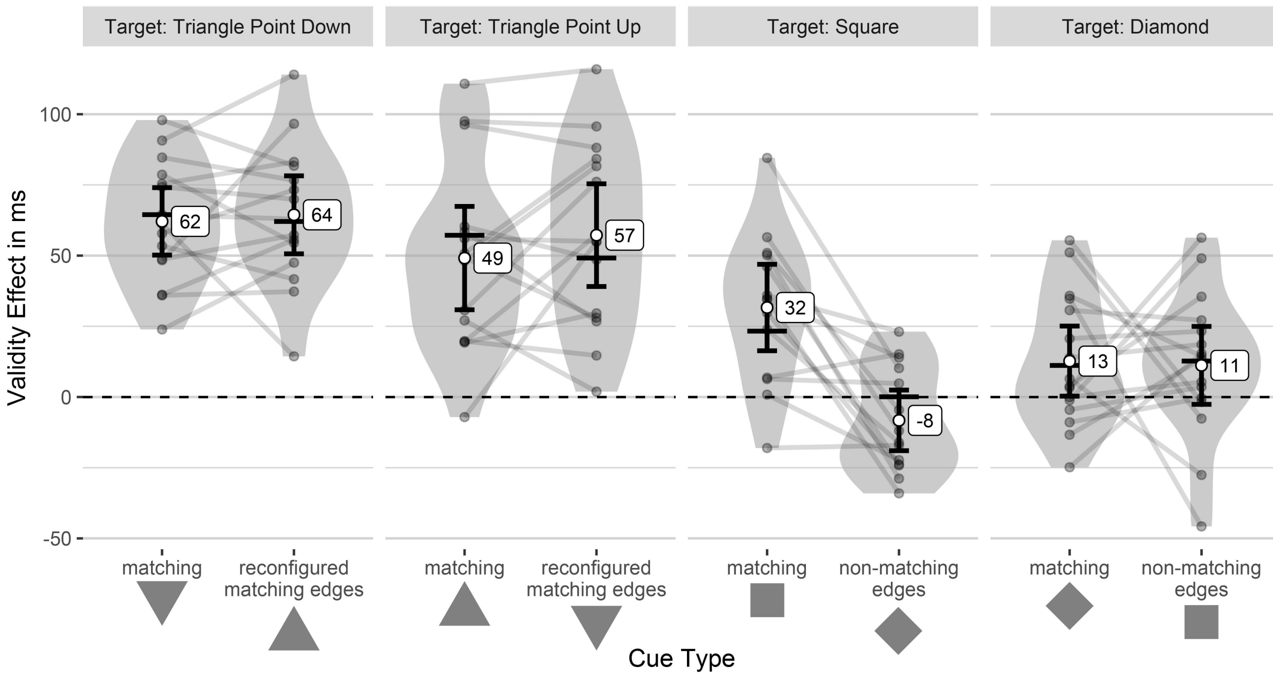
For the validity-effect analysis, we excluded 2.30% of all trials with reaction times below 150 ms and above 1 s and 13.21% of the remaining trials with wrong answers. These exclusions left us with 102 to 138 valid matching trials per participant (M = 123.33, SD = 9, Mdn = 124), and 103 to 137 (M = 125.80, SD = 8.74, Mdn = 127) valid trials with the other cue types.

Validity Effect

Initially, we wanted to collapse the data across the equilateral triangle variants and the square or diamond variants since we expected no difference between them (as in Experiment 2). However, we found a significant main effect of target shape with quadrangular targets. Therefore, we analyzed all target shape variants separately. Since neither the main effect nor the interaction of the factor order of blocks was significant, we analyzed the data collapsed across block orders. A Shapiro-Wilk test for normality showed that all validity effects and differences between validity effects were normally distributed (all p values above .43).

Figure 5

Validity Effects (Invalid Minus Valid Reaction Times) in Experiment 3



Note. The error bars represent the 95% CI for the one-sample *t* test against zero (dashed line). The wide error bars represent the 95% CI for the difference between the validity effects. The lowest and highest values have only one error bar since only one comparison is possible. Non-overlapping error bars indicate a significant difference.

For the triangle target shapes, we replicated Experiment 2 (significant validity effect for matching cues and reconfigured matching cues). However, this time, we found no significant difference between the validity effects, see Table A1 in the Appendix. For the square or diamond target shapes, we found a significant validity effect only for matching cues but not for cues with non-matching edges (45°-rotated version of the target shape). Additionally, when participants searched for the square, the validity effect was significantly higher for the matching cue compared to the cue with non-matching edges (diamond). This difference was not significant when the diamond was the target shape and the cue with non-matching edges was a square. Furthermore, the validity effects in the diamond-target condition were remarkably smaller than the other validity effects. Table A1 shows the results in detail, and Figure 5 shows the validity effects in each experimental condition.

Discussion

In Experiment 3, we replicated important results of Experiment 2 and tested whether cues without target-matching edges capture attention when they share the same (geometric) shape outline. When participants searched for an equilateral triangle, we found that the cue with reconfigured matching edges captured attention as strong as the matching cue. This replicated the most important finding of Experiment 2. More interesting are the conditions in which participants searched for a square or diamond. In these conditions, the 45°-rotated cue did not share any edges with the target shape. The results showed that in both target shape conditions, cues without target-matching edges did not capture attention while the matching cues did. However, only in the square target condition, the validity effect for the matching cue was significantly stronger than for the cue without target-matching edges. There was no significant difference between the two cue types in the diamond target condition.

Furthermore, the validity effect for the matching cue in the square target condition was more than twice as big as in the diamond target condition (13 vs. 32 ms). The small validity effect in the diamond target condition suggests that attentional control settings for diamonds were less effective in guiding attention than for other target shapes. A reason could be a higher similarity between the many oblique edges of distractors and target in the diamond target displays: Remember that upwards and downwards oriented equilateral triangles were used as distractors in the quadrangular target displays (see Table 1). Maybe it was impossible to apply effective attentional control settings for diamonds under such search conditions. Without top-down attentional control settings for one or more target features, all salient stimuli could capture attention. Since all cues were salient singletons in the cueing display, the small validity effect of both cue types in the diamond target condition would then be due to salience-driven attentional capture.

However, in the square target condition, where it seems that effective attentional control settings were established and applied before target onset, we found no attentional capture by diamond cues, with the same (geometrical) shape outline but different edge orientations than the target. Therefore, it seems that either the global shape outline cannot be used for attentional guidance if not at least some edges match those of the target (although the spatial arrangement could be different from the target), or that squares and diamonds are perceived as qualitatively distinct, despite sharing the same global shape (Clément & Bukley, 2008; Mach, 1922; Rock, 1974). If the classification of 45°-rotated squares as diamonds (and vice versa) allowed the attentional control settings to discriminate between these shapes despite being geometrically the same, it seems plausible that the categorically non-matching shape did not capture attention.

To further investigate the possibility of global shape outline as an attentional guiding feature, we used equilateral triangles again in Experiment 4 since triangles are perceived as triangles independent of their rotation. To include cues with the same global shape outline but without target-matching edges, we used 45°- and 90°-rotated equilateral triangles.

Table 2

Cueing and Target Displays of Experiments 4 to 7

Target Shape	Cue Types				Distractors
Experiment 4					
	46 ms**	61 ms**	65 ms**	63 ms**	
Experiment 5					
	31 ms*	27 ms**	13 ms*	10 ms	
Experiment 6					
	43 ms**	21 ms**	−4 ms	3 ms	
Experiment 7					
	62 ms**	66 ms**	45 ms**	63 ms**	

Experiment 4 displays:

Experiment 5 displays:

Experiment 6 displays:

Experiment 7 displays:

Note. In Experiments 4 and 6, the global shape orientation was not necessary to find the target shapes since they were the only triangle or trapezoid in the target display. In Experiment 5, the specific global shape orientation became task-relevant since the target had to be differentiated from distractor triangles in other orientations. In Experiment 7, the target trapezoid could appear in three different orientations, encouraging orientation-independent search for the global shape outline. Below the cue shapes is the validity effect and *p* value for the *t* test against zero.

* $p < .05$. ** $p < .001$.

Experiment 4

In Experiment 4, we used an equilateral triangle pointing upwards as target shape and four cues consisting of the same equilateral triangle in four different orientations (0°-, 45°, 90°, and 180° rotated). The 0°-rotated cue matched the target shape exactly, while the 180°-rotated cue consists of reconfigured matching edges. The 45°- and 90°-rotated cues consist of entirely differently oriented edges and only share their global shape outline with the target. If attentional guidance is based on target-matching edges (independent of their spatial arrangement), we expected validity effects for the matching cue and the cue with reconfigured matching edges (replicating Experiments 2 and 3). However, if the global shape outline can guide visual attention, we expect that all four cue types elicit significant validity effects since all cues share their global shape outline with the target. Table 2 provides an overview of the shapes used as the target, cue, and distractors in Experiments 4 to 7.

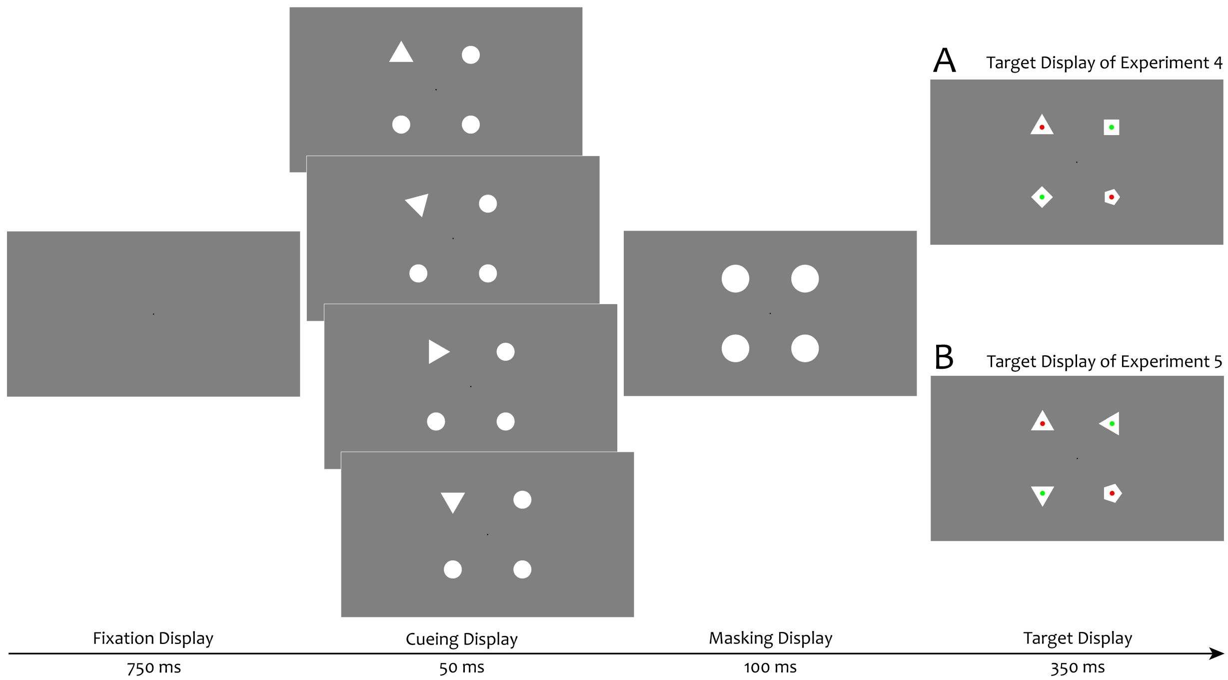
Method

Participants

In Experiment 4, we analyzed data from 22 participants (17 women, 5 men) aged between 18 and 30 years (*M* = 22.09, *SD* = 3.07, *Mdn* = 22). No participant was excluded due to a high error rate during practice. With 22 participants, this experiment achieved a power of 0.94 to find a validity effect of 20 ms. Details about the measurement precision and the simulation used for estimating the achieved power are presented in the Appendix.

Figure 6

Procedure of Experiment 4 (A) and Experiment 5 (B)



Note. Depicted are valid trials with all possible cue types. The target display A appeared in Experiment 4, the target display B in Experiment 5. All other displays were the same in Experiments 4 and 5. All stimuli are drawn to scale.

Design and Procedure

The design and procedure were similar to Experiment 3. Participants searched for an equilateral triangle pointing upwards. The cues were the same shapes as the target but rotated 0°, 45°, 90°, or 180° (within-subject variable with four levels). The 0°-rotated cue is the same as the target shape (matching), the 180°-rotated cue consists of reconfigured target-matching edges, and the 45°- and 90°-rotated cues share no edges with the target, but their global shape outline matches that of the target. The experiment consisted of 1,536 trials (96 valid and 288 invalid trials for each cue type) and lasted about 60 min. Figure 6A shows the procedure.

Stimuli

A simple pentagon with a side length of 2.13° (resulting in the same area as the other shapes) was used as a distractor instead of a hexagon or octagon. All other shapes were the same as in the previous experiments.

Results

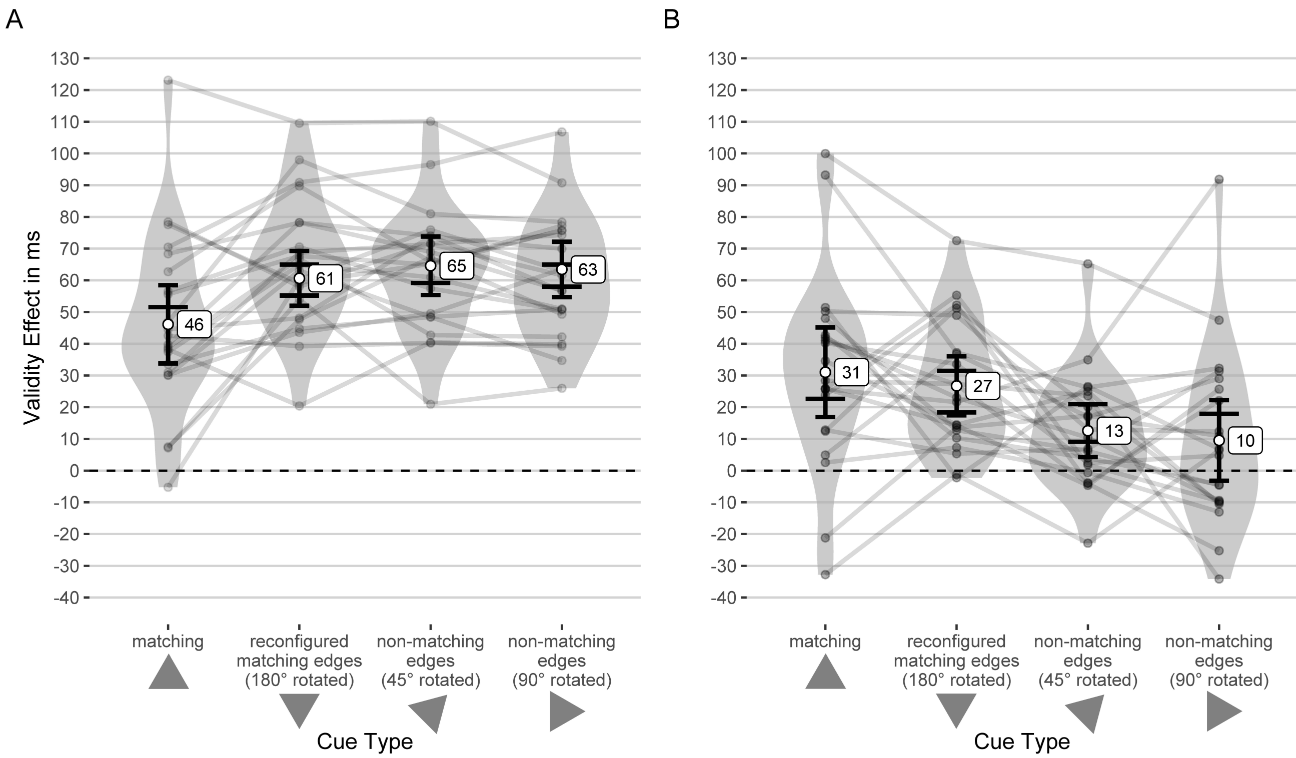
For the validity-effect analysis, we excluded 1.15% of all trials with reaction times below 150 ms and above 1 s and 5.26% of the remaining trials with wrong answers. These exclusions left us with 74 to 96 valid trials per participant across all four cue types (M = 88.59–89.50, SD = 4.54–5.18, Mdn = 90–91).

Validity Effect

A Shapiro-Wilk test for normality showed that all validity effects and differences between them were normally distributed (all p values above .29). We found significant validity effects for all cue types (46 ms, 61 ms, 65 ms, and 63 ms for the matching cue, the cue with reconfigured matching edges, the cues with non-matching edges [90°- and 180°-rotated], respectively). As in Experiment 2, the validity effect elicited by the matching cue was significantly smaller than all other cue types. There was no significant difference between all other cue types. Figure 7A shows the validity effects of all cue types, and Table A2 in the Appendix the detailed results, including all contrasts between the cue types.

Figure 7

Validity Effects (Invalid Minus Valid Reaction Times) in Experiment 4 (A) and Experiment 5 (B)



Note. The narrow error bars represent the 95% CI for the one-sample *t* test against zero (dashed line). The wide error bars represent 95% CI for all comparisons. The lowest and highest values have only one error bar since only one comparison is possible. Non-overlapping error bars indicate a significant difference.

Discussion

In Experiment 4, we confirmed that the global shape outline can be a guiding feature for visual attention. However, the results of Experiment 3 provided no evidence for such guidance. When participants searched for a square, a diamond cue did not capture attention despite having the same geometrical global shape outline as a square. Maybe the attentional control settings differentiated between squares and diamonds as these shapes are perceived as qualitatively distinctive, although these shapes share the same global outline (Clément & Bukley, 2008; Mach, 1922; Rock, 1974). This peculiarity of shapes and diamonds was the reason for Experiment 4 where we used equilateral triangles as targets. Triangles are always perceived as triangles independent of their orientation. In Experiment 4, 45° and 90° rotated triangles served as cues that shared the global shape outline with the target but without sharing any edge orientation.

We found that cues without target-matching edges (45°- and 90°-rotated triangles) elicited strong validity effects, similar to the cue with reconfigured matching edges and even stronger than the target-matching cue. These results indicate that the global shape outline can guide visual attention as long as a differently rotated version of the searched-for shape is not perceived or classified as an entirely different shape.

However, one caveat is that these results are also compatible with bottom-up, salience-driven capture by the cues. We would expect such capture if no functional top-down attentional control settings were established during the search task. Without top-down attentional control settings, all salient stimuli would capture attention. However, this is unlikely since we found no validity effect of a non-matching cue in Experiment 1, where we presented a non-matching shape cue (a hexagon) in addition to the matching cue. Five participants searched for the same target shape as in Experiment 4 (an equilateral triangle pointing upwards), allowing a comparison with the present experiment. While the matching cue elicited a significant validity effect similar to the cues in Experiment 4 (58 ms, $p = .009$), the non-matching cue did not elicit a significant validity effect (−8 ms, $p = .11$). The difference between the validity effects was significant (Δ 66 ms, p = .007). These results suggest that the validity effects in Experiment 4 were not due to bottom-up capture of the singleton cues. We would have also expected bottom-up capture to elicit much smaller validity effects (cf. Büsel et al., 2020), which is why we mentioned such capture as a possible explanation of the small and unspecific validity effects in the diamond target condition of Experiment 3.

In the next experiment, we tested whether the global shape outline always guides attention if participants search for a shape. Is the shape representation used as attentional template orientation-invariant? Can top-down effects like search goals influence the role of orientation in this shape template? In Experiment 5, the target was an equilateral triangle pointing upwards (as in Experiment 4), but it was presented together with equilateral triangles in other orientations as distractors. Therefore, searching for the global shape outline of a triangle would not allow finding the target. Instead, participants had to search for the specific pointing direction of the target triangle. Using the same cue types as in Experiment 4, we can measure the effect of pointing-specific search templates on attentional guidance compared to Experiment 4, where the global shape outline was enough to find the target.

Experiment 5

In Experiment 5, we investigated whether a shape pointing in a specific direction can be used as a template and guide visual attention if the task requires finding an equilateral triangle based on its unique pointing direction. We repeated Experiment 4 with two small changes. In the target display, we replaced the square with an equilateral triangle pointing left (270°-rotated), and the diamond with an equilateral triangle pointing right (180°-rotated). In this situation, participants could no longer search for the target by its global shape outline. Instead, participants had to search for the specific pointing direction (i.e., the triangle pointing upwards). If attentional guidance can be tuned to a specific target pointing direction, only the matching cue should capture attention since it is the only cue with the same pointing direction as the target. However, if the target's global outline remains the guiding feature, all cues should capture attention (as in Experiment 4).

Method

Participants

We analyzed data from 21 participants (16 women, 5 men) aged between 18 and 24 years (M = 21.14, SD = 1.82, Mdn = 21) in Experiment 5. One participant did not reach 80% accuracy within 10 min of practice and, thus, was excluded before data collection started. Additionally, we excluded one participant with an error rate of 41.93% (although no outlier due to a one-sided Grubbs test, p = .085, this error rate was 9.25 percentage points higher than the second-highest error rate and close to chance performance at 50%). With 21 participants, this experiment achieved a power of .90 to find a validity effect of 20 ms.

Design and Procedure

Procedures of Experiments 4 and 5 were the same, except that two other equilateral triangles (270°-rotated [pointing to the left] and 180° rotated [pointing downwards], respectively) replaced the diamond and square as distractors in the target display. Therefore, the participants had to search for a specific pointing direction, see Figure 6B.

Results

For the validity-effect analysis, we excluded 3.5% of all trials with reaction times below 150 ms and above 1 s and 16.35% of the remaining trials with wrong answers. These exclusions left us with 61 to 95 valid trials per participant across all four cue types (*M* = 78.48–79.62, *SD* = 7.88–8.17, *Mdn* = 78–82).

Validity Effect

A Shapiro-Wilk test for normality showed that all validity effects and differences between them were normally distributed (all *p* values above .082). We found that matching cues and reconfigured matching cues elicited significant and strong validity effects (31 and 27 ms, respectively, *p* values ≤ .001). The validity effect of the cue with non-matching edges (45° rotated) was much smaller (13 ms) but also significantly different from zero (*p* = .014). A similar validity effect was elicited by the 90°-rotated cue with non-matching edges (10 ms). However, this validity effect was not significantly different from zero (*p* = .28). The validity effect of the matching cues was significantly stronger than those of the 45° and 90° rotated cues (*Δ* 18 and 14 ms, both *p* values 0.43). All other differences were non-significant. Figure 7B and Table 3 show the validity effects and contrasts, including unbiased effect sizes and 95% CIs.

Discussion

Experiment 5 was a follow-up of Experiment 4. In Experiment 4, the results suggested that participants can use the global shape outline as feature to guide visual attention. Equilateral triangles captured attention even if they shared no edge orientation

Table 3

Mean Validity Effects for Each Cue Type in Experiment 5

Cue Type	*M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
matching	31 (31)	[17, 45]	4.58(20)	.001	0.96	[0.46, 1.52]
180° rotated	27 (20)	[17, 36]	5.99(20)	< .001	1.26	[0.71, 1.89]
45° rotated	13 (18)	[4, 21]	3.16(20)	.014	0.66	[0.20, 1.16]
90° rotated	10 (28)	[−3, 22]	1.56(20)	.28	0.33	[−0.10, 0.78]
Contrasts						
matching vs. 180° rotated	4 (29)	[−9, 17]	0.69(20)	1.00	0.14	[−0.28, 0.58]
matching vs. 45° rotated	18 (25)	[7, 30]	3.37(20)	.043	0.71	[0.24, 1.21]
matching vs. 90° rotated	22 (38) [b]	[4, 39]	2.58(20)	.085	0.54	[0.09, 1.02]
180° rotated vs. 45° rotated	14 (21)	[5, 24]	3.08(20)	.043	0.65	[0.19, 1.14]
180° rotated vs. 90° rotated	17 (32)	[3, 32]	2.46(20)	.085	0.52	[0.07, 0.98]
45° rotated vs. 90° rotated	3 (26)	[−9, 15]	0.53(20)	1.00	0.11	[−0.31, 0.54]

Note. Mean and *SD* in ms.

[a] Adjusted using the procedure of Benjamini and Yekutieli (2001).

[b] This value deviate slightly from the difference between the rounded means since the latter contain rounding errors.

with the target. In Experiment 5, we tested whether an equilateral triangle pointing in a specific direction can selectively capture attention if the task requires search for such a target amongst equilateral triangles pointing in different directions.

The results indicate that the pointing direction of an equilateral triangle is not as effective in guiding visual attention as the global shape outline. Although the search task required distinguishing between an equilateral triangle pointing upwards (the target) and an equilateral triangle pointing downwards (180° rotated, one of three distractors), the 180°-rotated cue captured attention as strong as the matching cue. However, the results also suggest that searching for a specific pointing direction influenced attentional control settings since the other two cue types elicited much smaller validity effects than the matching and 180°-rotated cues. To further analyze the influence of the different search tasks,[4] we conducted unequal variances *t* tests (Welch's *t* test) for significant differences between the validity effects in Experiment 4 (where the pointing direction of the target was irrelevant) and Experiment 5 (where a specific pointing direction was task-relevant). The results showed that in Experiment 5, all cue types elicited significantly smaller validity effects than in Experiment 4, except for the matching cue, where the difference was non-significant (see Table 4 for all comparisons).

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[4] Note that the search task changed only due to the inclusion of two differently oriented equilateral triangle distractors to the target display. The instruction was exactly the same in Experiments 4 and 5. This shows the influence of the target-distractor relations on attentional control settings (mediated through the search task). However, all cues were presented among neutral non-singleton stimuli before the target display. Therefore, attentional capture by the cues was not directly influenced by the target-distractor relationships and only via the templates directed to the targets. This is different from visual search protocols.

Table 4

Mean Validity Effects Differences Between Experiments 4 and 5 for Each Cue Type

Contrasts [b]	Δ *M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
matching	15 (29)	[−3, 33]	1.68(40.05)	.21	0.50	[−0.10, 1.12]
reconfigured matching edges (180° rotated)	34 (20)	[22, 46]	5.57(40.61)	< .001	1.67	[0.99, 2.40]
non-matching edges (45° rotated)	52 (20)	[40, 64]	8.72(40.72)	< .001	2.60	[1.82, 3.47]
non-matching edges (90° rotated)	54 (24)	[39, 69]	7.29(35.80)	< .001	2.20	[1.46, 3.00]

Note. Mean and *SD* in ms. *SD* is the pooled variance.

[a] Adjusted using the procedure of Benjamini and Yekutieli (2001).

[b] Validity effect in Experiment 4 minus validity effect in Experiment 5 for each cue type.

The significant differences between Experiments 4 and 5 indicate that the search for a specific pointing direction in Experiment 5 significantly reduced the attentional capture of cues with a different pointing direction (45°- and 90°-rotated triangles) compared to Experiment 4 (although, in Experiment 5, the 45°-rotated cue still elicited a small but significant validity effect). However, it seems that the established attention control settings for equilateral triangles pointing upwards could not differentiate between matching cues and 180°-rotated cues pointing in the opposite direction (both elicited strong validity effects). Therefore, the feature that guided visual attention in Experiment 5 must have been present in both these cue types.

Basically, to search for the pointing direction of the target triangle, participants could have used two types of information: a locally more refined characteristic – the sharp angle of the triangle – and the triangle's global orientation (relative to which the sharp angle could be located). Since the matching and 180°-rotated cue shared their global orientation (e.g., derived from the symmetry axis dividing the base midway), this seems to be the template that participants used in a first step before deciding about the location of the sharp end relative to this global orientation. In line with this interpretation, there is evidence that global shape orientation is a primary guiding feature for attention during visual search for shapes (cf. Enns & Rensink, 1991; Found & Müller, 1997). Especially vertical mirror symmetry axis is a salient shape feature (cf. Wagemans, 1995; Wenderoth, 1994), and, thus, a plausible template for effective attentional guidance. However, as global shape orientation can also be derived from local characteristics like a symmetry axis, a prolonged axis, or parallel lines (Chaisilprungraung et al., 2019; Palmer, 1985; Sekuler, 1996; Wiser, 1981), there is a tight connection between local characteristics and global shape orientations. Therefore, we believe that it depends on the difficulty with which global orientation or local characteristics become available for participants' decision about which of the two they use in a first step of guidance toward pointing-direction or orientation defined targets.

The results of Experiment 5 provide supporting evidence for global shape orientation as an attentional guiding template since the matching and 180°-rotated cues shared the same global shape orientation (based on their vertical mirror symmetry axis). Furthermore, the lack of a significant difference between these cue types indicates that local shape features alone did not explain attentional guidance. Otherwise, the validity effect would have been stronger for matching cues compared to 180°-rotated cues.

The small validity effects elicited by 45°- and 90°-rotated cues (with non-matching global shape orientation based on their mirror symmetry axis) indicated that attentional selectivity for global shape orientation was not perfect. Completely ignoring these cues might have been difficult or impossible since equilateral triangles are multistable figures. They have three identical mirror symmetry axes, and, thus, a single equilateral triangle can be perceived as pointing at any one of three possible directions (cf. Attneave, 1968). Therefore, the local characteristics alone cannot easily be used to derive an unambiguous pointing direction. This relates back to the argument above that it probably depends on the difficulty of discriminating between the local and the global characteristics. In essence, participants need some more time to decide which of three local angles is more pointed if the angles are relatively similar. In the case of an equilateral triangle, contextual information provides a frame of reference to perceive a specific orientation and pointing direction (cf. Palmer, 1980). Without contextual information, the vertical direction of gravity might be preferentially used as a frame of reference (cf. Clément & Bukley, 2008; Rock, 1974). These aspects make it difficult to parse the orientation and pointing direction of an equilateral triangle, especially within the 50 ms the cues were presented. As a result, the pointing direction could not be used as a guiding feature for attention, and the global shape orientation guided attention partially, with residual validity effects for triangles in a non-matching orientation.

If these results are due to the ambiguous nature of equilateral triangles, search for shapes with one unambiguous principal axis and local features that unambiguously indicate a pointing direction should elicit a different attentional control setting. For example, if it is easier to parse orientation and direction information, these features might guide visual attention even if they are unnecessary to find the target. In Experiment 6, we used isosceles trapezoids as the target shape to test these predictions.

Experiment 6

Experiment 6 was essentially the same as Experiment 4 but with an isosceles trapezoid as the target shape. Isosceles trapezoids are also simple 2D shapes and not vastly different from equilateral triangles. However, their geometrical structure includes unambiguous information about the direction of the shape: The longer edge of the two parallel edges is always the base of the trapezoid. Furthermore, an isosceles trapezoid has only one mirror symmetry axis (perpendicular to its parallel edges). Using cues with different orientations than the target shape, we tested whether orientation and direction information is used for attentional guidance if these features are unambiguously embedded within the geometrical structure of a shape.

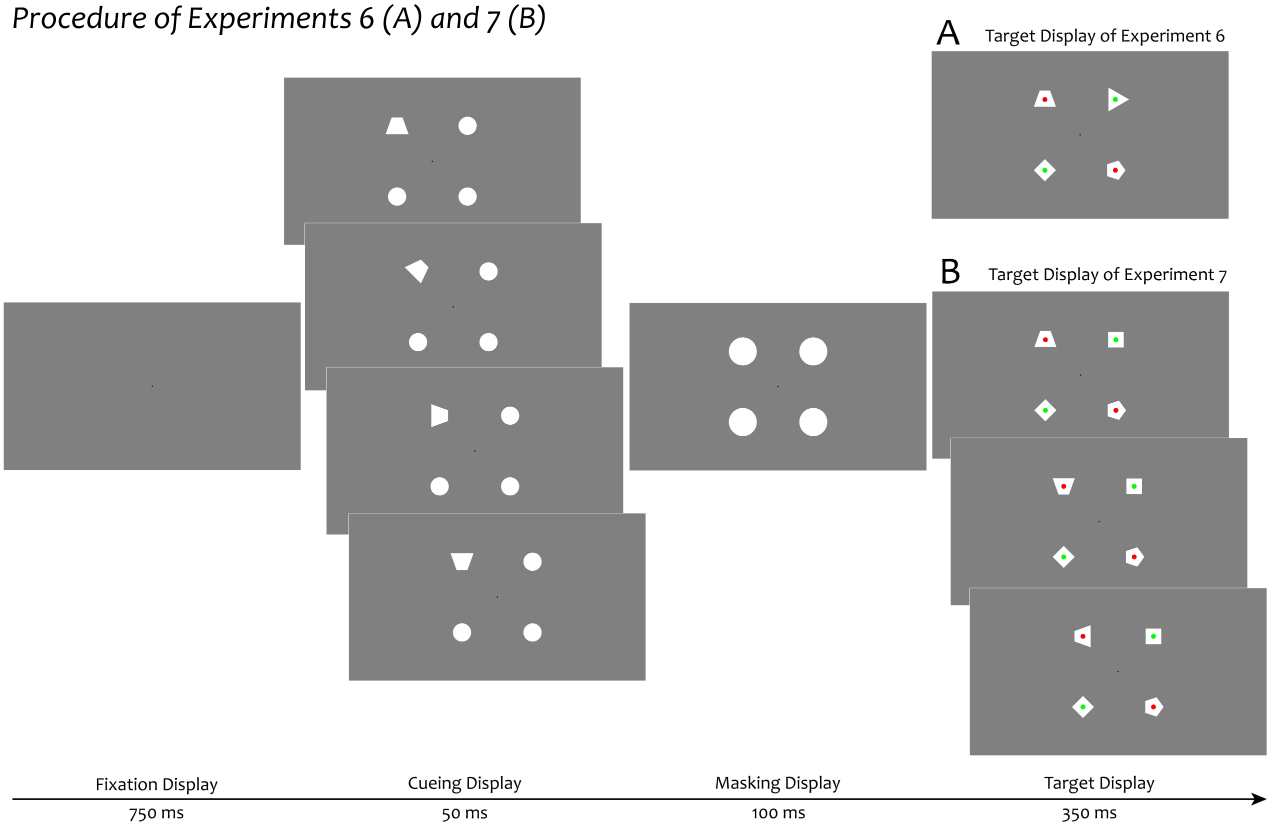
Method

Participants

We analyzed data from 18 participants (12 women, 6 men) aged between 19 and 32 years (*M* = 22.89, *SD* = 3.41, *Mdn* = 22.5). One participant did not reach 80% accuracy within 15 min of practice and was excluded before data collection started. Three participants

Figure 8

Procedure of Experiments 6 (A) and 7 (B)



Note. Depicted is a valid trial with all possible cues for Experiment 6 (Target Display A) and Experiment 7 (Target Display B). Except for the target displays, all stimuli were the same in Experiments 6 and 7. All stimuli are drawn to scale.

were excluded after data collection since their error rates (51.76, 34.83%, and 28.52%) were outliers according to a one-sided Grubbs test (p = .001, p = .024, and p = 0.049, respectively). With 18 participants, this experiment achieved a power of .86 to find a validity effect of 20 ms.

Design and Procedure

The design and procedure were similar to Experiment 4, except that participants searched for a convex isosceles trapezoid with the base at the bottom amongst three distractor shapes (a 90°-rotated equilateral triangle, a diamond, and a pentagon). Since the target was the only trapezoid in the target display, it was unnecessary to search for a specific target orientation. The cues were the same shapes as the target and either matching or 45°, 90°, or 180° rotated (within-subject variable with four levels). The experiment consisted of 1,536 trials (96 valid and 288 invalid trials for each cue type) and lasted about 60 min. Figure 8A shows the procedure.

Stimuli

Except for the trapezoid, all shapes were the same as in the previous experiments. The top of the trapezoid was 1.87°, the base 3.95°, and the legs 3.09° long.[5]

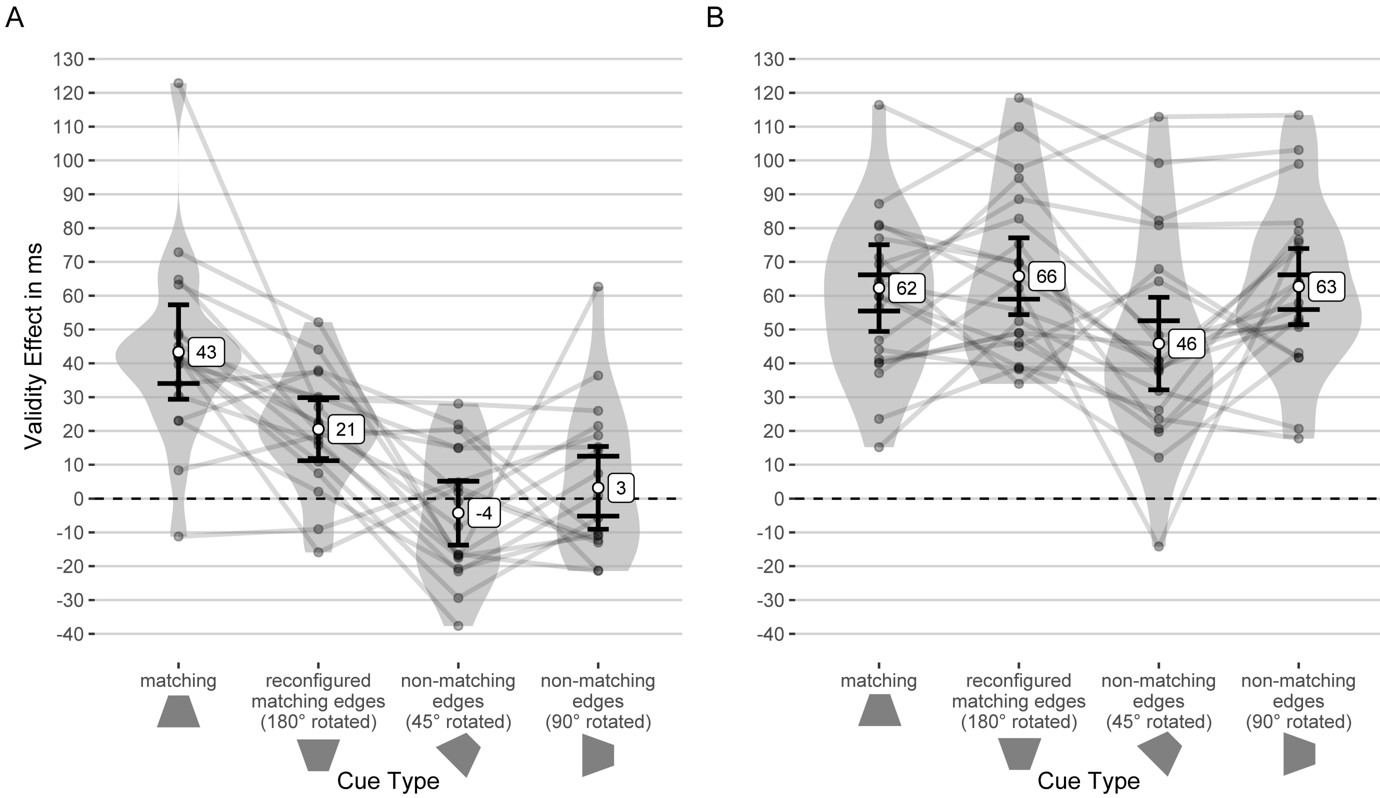
Results

For the validity-effect analysis, we excluded 2.35% of all trials with reaction times below 150 ms and above 1 s and 4.77% of the remaining trials with wrong answers. These

[5] Due to a calculation error, the area of the trapezoids was unintentionally 8% bigger than the area of the other shapes. It seems plausible that this difference was not noticeable (see Figure 8, where the trapezoids are drawn to scale, for comparison). If we assume that the participants consistently perceived the trapezoid as the biggest shape, this would even strengthen our results. The participants could then have used a singleton search mode or a size-search mode to find the trapezoid target, and all cues would have captured attention since they were all singletons (cf. Bacon & Egeth, 1994) and they were all of the same size as the targets: Yet, we found only significant validity effects for the matching and 180°-rotated trapezoid cues during search for trapezoid targets.

Figure 9

Validity Effects (Invalid Minus Valid Reaction Times) in Experiment 6 (A) and Experiment 7 (B)



Note. The narrower error bars represent the 95% CI for the one-sample *t* test against zero (dashed line). The wider error bars represent 95% CI for all mean comparisons. The lowest and highest values have only one error bar since only one comparison is possible. Non-overlapping error bars indicate a significant difference.

exclusions left us with 70 to 94 valid trials per participant across all four cue types (M = 83.5–85.22, SD = 4.51–6.25, Mdn = 83.5–87).

Validity Effect

A Shapiro-Wilk test for normality showed that all validity effects and differences between them were normally distributed (all *p* values above .084). The fully matching (0°-

rotated) cue and the 180°-rotated cue elicited a significant validity effect (43 and 21 ms, respectively). The difference between these cues was significant (p = .006). The other two cues did not elicit significant validity effects (−4 and 3 ms for 45°- and 90°-rotated cues, respectively). The difference was non-significant (p = .63), but the validity effects of both cues were significantly smaller than those elicited by the matching and 180°-rotated cues (all p values ≤ .021). Table 5 shows the detailed results, and Figure 9A depicts the validity effects.

Discussion

In Experiment 6, we used an isosceles trapezoid as the target shape while otherwise using the same procedure and design as in Experiment 4. Isosceles trapezoids contain unambiguous information about their directions and have only one mirror symmetry axis, unlike the equilateral triangle used as target shape in Experiment 4. We investigated whether global (pointing) orientations are used as attentional guiding feature even if they are not necessary to find the target. In Experiment 4, we found that during such a search for equilateral triangles, attention was guided by the global shape outline, independent of the target orientation.

However, with isosceles trapezoids as the target, we found that matching and 180°-rotated cues elicited significant validity effects, while 45°- and 90°-rotated ones did not. These results are similar to those of Experiment 5. It seems that the easier available global shape orientation and direction information influences attentional guidance even if this information is not needed to identify the target. However, attentional guidance was still not entirely selective for the pointing direction of the target trapezoid (base at the bottom). The

Table 5

Mean Validity Effects and Contrasts for Each Cue Type in Experiment 6

Cue Type	*M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
matching	43 (28)	[29, 57]	6.55(17)	< .001	1.47	[0.84, 2.22]
180°-rotated	21 (18)	[12, 29]	4.97(17)	< .001	1.12	[0.56, 1.77]
45°-rotated	−4 (19)	[−14, 5]	−0.94(17)	1.00	−0.21	[−0.68, 0.25]
90°-rotated	3 (25)	[−9, 15]	0.55(17)	1.00	0.12	[−0.34, 0.59]
Contrasts						
matching vs. 180°-rotated	23 (26) [b]	[10, 36]	3.72(17)	.006	0.84	[0.32, 1.41]
matching vs. 45°-rotated	48 (39) [b]	[28, 67]	5.20(17)	.001	1.17	[0.60, 1.83]
matching vs. 90°-rotated	40 (36)	[22, 58]	4.78(17)	.001	1.08	[0.52, 1.71]
180°-rotated vs. 45°-rotated	25 (24)	[13, 37]	4.35(17)	.002	0.98	[0.44, 1.59]
180°-rotated vs. 90°-rotated	17 (24) [b]	[5, 29]	3.05(17)	.021	0.69	[0.19, 1.23]
45°-rotated vs. 90°-rotated	−7 (27)	[−21, 6]	−1.17(17)	.63	−0.26	[−0.74, 0.20]

Note. Mean and *SD* (in parentheses) in ms.

[a] Adjusted using the procedure of Benjamini and Yekutieli (2001).

[b] These values deviate slightly from the difference between the rounded means since the latter contain rounding errors.

180°-rotated cue (with the base at the top) elicited a validity effect significantly stronger than zero but significantly smaller than the matching cue. The pointing direction influences attentional guidance to some degree, while the mirror symmetry axis was evidently the guiding feature. Therefore, matching and 180°-rotated cues, which share their mirror symmetry axis with the target (and, thus, the global shape orientation), both captured attention. Cues with a non-matching global orientation did not capture attention.

The results of Experiment 6 corroborate the hypothesis that the mirror symmetry of a shape can guide visual attention. However, we did not find evidence for attentional guidance by global shape outline as in Experiment 4, although the target was not defined by a specific orientation or pointing direction. This raises the question of whether effective attentional guidance by global shape outline is limited to multistable figures like equilateral triangles, where a specific orientation and pointing direction is ambiguous. Therefore, in Experiment 7, we repeated Experiment 6 with a different search task, where search for the global shape outline is invited.

Experiment 7

To test whether search for isosceles trapezoids can elicit attentional control settings sensitive to the global shape outline, we invited the search for a trapezoid independent of any specific orientation (i.e., its global shape outline). Across trials, each participant searched for a target trapezoid in different shape orientations: There was only one trapezoid in each target display, but it was randomly 0° rotated (as in Experiment 6), 180° rotated, or 270° rotated (see Figure 8B). This procedure should encourage participants to search for trapezoids of several orientations, as indicated by analog manipulations of the number of to-be-searched for target colors (cf. Ansorge & Horstmann, 2007; Irons et al., 2012; Kerzel & Witzel, 2019). Here, we hoped to encourage the participants to set up attentional control settings for the global shape outline of the trapezoid, independent of its orientation (cf.

Shinar & Owen, 1973), as an economical alternative to several search templates for differently oriented trapezoids.

To differentiate between attentional control settings for the three possible target orientations and the global shape orientation of the trapezoid, we deliberately used only three possible target orientations instead of presenting the trapezoid with a random orientation. This ensured that the 45°- and 90°-rotated cues never matched the target orientation. If the participants searched only for the three target orientations, then only the correspondingly rotated cues should have captured attention, while the 45°- and 90°-rotated cues should not. However, if participants searched for the global shape outline of the trapezoid and the attentional control setting can be tuned to the global shape outline, all cues (0°, 45°-, 90°-, and 180°-rotated) should have captured attention.

Method

Participants

In Experiment 7, we analyzed data from 21 participants (13 women, 8 men) aged between 19 and 28 years (M = 21.43, SD = 2.75, Mdn = 20). No participant was excluded after data collection. With 21 participants, this experiment achieved a power of .92 to find a validity effect of 20 ms.

Design and Procedure

The procedure of Experiment 7 was the same as in Experiment 6, except that the target trapezoid was randomly 0°, 180°, or 270° rotated. Thus, the participants were encouraged to search for the trapezoid independently of its orientation. The stimuli were the same as in Experiment 6, see Figure 8B. The experiment consisted of 1,536 trials (96 valid and 288 invalid trials for each cue type) and lasted about 60 min.

Results

We excluded 2.03% of all trials with reaction times below 150 ms and above 1 s and 12.04% of the remaining trials with wrong answers for the validity-effect analysis. These exclusions left us with 75 to 95 valid trials per participant across all four cue types (M = 85.62–87.14, SD = 4.20–4.68, Mdn = 85–88).

Validity Effect

A Shapiro-Wilk test for normality showed that all validity effects and differences between them were normally distributed (all p values above .14). We found significant validity effects for all cues (62, 66, 45, and 63 ms for the 0°, 180°-, 45°-, and 90°-rotated cues, respectively). The validity effect of 45°-rotated cues was significantly smaller than the validity effects of other cue types (all p values < .046). All other differences were non-significant (all p values = 1.00). Figure 9B and Table 6 show the validity effects and contrasts, including unbiased effect sizes and 95% CIs.

Discussion

In Experiment 7, participants searched for a trapezoid, which could occur in three possible orientations. This invited search for the global shape outline of the target, regardless of its orientation, instead of search based on a specific global shape orientation.

Table 6

Mean Validity Effects and Contrasts for Each Cue Type in Experiment 7

Cue Types	*M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
0°-rotated	62 (28)	[49, 75]	10.12(20)	< .001	2.13	[1.40, 3.00]
180°-rotated	66 (25)	[54, 77]	12.09(20)	< .001	2.54	[1.71, 3.55]
45°-rotated	45 (30)	[32, 60]	6.98(20)	< .001	1.47	[0.88, 2.15]
90°-rotated	63 (25)	[51, 74]	11.63(20)	< .001	2.44	[1.64, 3.42]
Contrasts						
0°-rotated vs. 180°-rotated	4 (21)	[−13, 6]	−0.76(20)	1.00	−0.16	[−0.59, 0.27]
0°-rotated vs. 45°-rotated	16 (26) [b]	[5, 28]	2.91(20)	.046	0.61	[0.16, 1.10]
0°-rotated vs. 90°-rotated	0 (20) [b]	[−10, 9]	−0.01(20)	1.00	−0.02	[−0.45, 0.41]
180°-rotated vs. 45°-rotated	20 (25) [b]	[9, 31]	3.66(20)	.023	0.77	[0.30, 1.28]
180°-rotated vs. 90°-rotated	3 (20)	[−6, 12]	0.69(20)	1.00	0.14	[−0.28, 0.58]
45°-rotated vs. 90°-rotated	−17 (27) [b]	[−29, −5]	−2.87(20)	.046	−0.60	[−1.09, −0.15]

Note. Mean and *SD* in ms.

[a] Adjusted using the procedure of Benjamini and Yekutieli (2001).

[b] These values deviate slightly from the difference between the rounded means since the latter contain rounding errors.

We found that all cues captured attention. Critically, the 45°- and the 90°-rotated cues elicited strong validity effects, although the target never occurred in these two orientations. Therefore, we can rule out that the participants established attentional control settings for only the three global shape orientations of the target.

Table 7

Mean Validity Effects Differences Between Experiments 6 and 7 for Each Cue Type

Contrasts [b]	Δ *M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
0°-rotated (matching)	19 (28)	[1, 37]	2.09(36.13)	.091	0.66	[0.02, 1.32]
180°-rotated	45 (22)	[31, 59]	6.62(35.72)	< .001	2.03	[1.28, 2.85]
45°-rotated	50 (26)	[34, 66]	6.28(34.37)	< .001	1.91	[1.17, 2.71]
90°-rotated	60 (25)	[43, 76]	7.52(36.14)	< .001	2.36	[1.57, 3.24]

Note. Mean and *SD* in ms. SD is the pooled variance.

[a] Adjusted using the procedure of Benjamini and Yekutieli (2001).

[b] Validity effect in Experiment 7 minus validity effect in Experiment 6 for each cue type.

The results showed that global shape outline could guide visual attention if participants search for the global shape outline of a trapezoid. Without the necessity to search for trapezoids in an orientation-unspecific way, attentional guidance is influenced by the mirror symmetry axis and local features indicating the pointing direction (see Experiment 6). We analyzed the differences of validity effects in Experiments 6 and 7 using unequal variances *t* tests (Welch's *t* test). The results showed that in Experiment 7, all cue types elicited significantly stronger validity effects than in Experiment 6, except for the 0°-rotated cue, where the difference was non-significant. Although the 45°-rotated cue elicited significantly smaller validity effects than those of other cue types in Experiment 7, it was significantly stronger than in Experiment 6 (see Table 7 for all comparisons).

General Discussion

In a series of experiments, we investigated whether the global shape outline and specific pointing directions of shapes can be guiding features for visual attention. While shape is considered as probably guiding visual attention efficiently, per definition, shapes consist of a combination of simpler features (e.g., points of maximum curvature, the orientations of edges, concavity or convexity of edges), and it is unclear whether such local features of a shape guide attention or whether global features like the global shape outline or the global shape orientation do (cf. Wolfe & Horowitz, 2004, 2017). Regarding the global features, earlier research provided inconclusive evidence. For example, Wolfe and Bennet (1997) observed that visual search for a target defined by its unique global shape was difficult and concluded that shapes are represented as bundles of local features before visual attention is deployed. These findings indicate that a global shape outline could not guide visual attention efficiently and is maybe even only derived from different local features after the attentional selection of a stimulus. However, Donnelly et al. (2000) showed that if distractors were homogenous, search for a target defined by its global shape outline could be efficient. Found and Müller (1997) found a similar influence of distractor homogeneity during the search for a uniquely oriented target shape: The search was only efficient if the distractor shapes were homogenously oriented. This substantial influence of distractors' homogeneity on search efficiency indicates that visual search experiments might not be the best way to investigate if and how features guide visual attention. Therefore, we used a contingent-capture protocol, arguing that visual search times and their relationship to set sizes are confounded by imperfect memory for already scanned positions (e.g., Husain et al., 2001), by overt eye movements and concomitant phases of reduced target visibility (cf. Findlay & Gilchrist, 1998), and by the contributions of distractor-directed suppression strategies to the estimates of attentional dwelling (cf. Rauschenberger & Yantis, 2006). All these problems are attenuated in the contingent-capture protocol where the same processes are studied using a single cue per trial that is more or less similar to the searched-for target and serves as a probe of the attentional control settings.

In Experiment 1, we demonstrated that the validity effect in the contingent-capture protocol is sensitive to attentional control settings during search for shapes. We showed that the target-matching cue captured and kept attention. In contrast, the 150-ms interval between cue and target was at least sufficient to ignore the non-matching but salient shape singletons entirely. This result appears to be in line with earlier claims of attentional capture by target-matching shapes (e.g., Adamo et al., 2010; Berggren & Eimer, 2018; Biderman et al., 2017; Lien et al., 2010; McCants et al., 2018).

Our first question concerned the role of oriented edges. Theoretically, in many situations participants could successfully search for 2D shapes by looking for one of several of the oriented edges. In Experiments 2 and 3, we found that cues with spatially reconfigured target-matching edges also captured attention, indicating that attentional guidance by shapes is not based on the exact combination of positions of oriented edges (cf. Wolfe & Bennet, 1997). In fact, the results of Experiment 4 showed that the global shape outline could be used to guide visual attention. When participants searched for an equilateral triangle, cues with the same global shape outline as the target captured attention, even if they shared no edge orientation with the target shape.

Our second question concerned the flexibility and malleability of attentional control settings for the inclusion of 2D shape orientations. In Experiment 5, we investigated whether search goals can modify the orientation-unspecific guidance by the global shape outline.

Participants had to search for an equilateral triangle with a specific pointing direction amongst distractor triangles pointing in alternative directions. The results indicated that a specific pointing direction could not be used for attentional guidance to target shape orientations only. Instead, we found strong validity effects for the target-matching and the 180°-rotated triangle (which pointed in the opposite direction of the target) and smaller but significant validity effects for the 45°- and 90°-rotated triangles. We concluded that the global shape orientation, derived from the vertical mirror symmetry axis, was the feature that initially guiding visual attention to oriented triangles the most (Experiment 5): Only the target-matching and the 180°-rotated triangle shared their mirror symmetry axis with the target shape, and, thus, captured attention most reliably.

In Experiments 6 and 7, we used a similar rationale but a different target shape: an isosceles trapezoid. In contrast to equilateral triangles, isosceles trapezoids have only one mirror symmetry axis and local features that unambiguously indicate the top and base of the shape. We hypothesized that attentional control settings of isosceles trapezoids might, therefore, include these orientation- or pointing-specific features by default, even if the target is not defined by a specific orientation. The results were similar to that in Experiment 5: Target-matching and 180°-rotated cues captured attention while 45°- and 90°-rotated cues did not or less so. These findings indicate that the mirror symmetry axis guided attention since all cues with the same mirror symmetry axis as the target elicited significant validity effects. In the final Experiment 7, we tested whether search goals could change attentional control settings towards the global shape of an isosceles trapezoid. Participants searched for an isosceles trapezoid that could appear in different orientations, inviting search for the global shape outline, independent of any specific orientation. The results showed that this search task led to attentional guidance by the global shape outline, as all trapezoid cues captured attention, independent of their orientation. Thus, both search for triangles and for trapezoids allowed top-down adjustments of attentional control settings, such that attention was either initially guided to the 2D target shape orientation or to the global 2D target shape outline, regardless of its orientation.

To sum up, we found evidence that the global shape outline and global shape orientation can be guiding features for visual attention. Which of these features is preferentially used seems to depend on the nature of the target shape and on target-distractor differences. In our study, shapes with an unambiguous (mirror) symmetry axis and local features that clearly indicate the top or bottom were seemingly represented in attentional control settings in a way that includes orientation information by default. In contrast, for shapes with ambiguous (i.e., context-dependent) orientation and position information, it seemed that attentional control settings were sensitive to the global shape outline without such orientation information. However, in both cases, we found that the default guiding feature changed depending on the search goal, showing that top-down effects can overrule stimulus-specific preferences for orientation-specific or -unspecific attentional guidance. Both, the stimulus-specific default attentional control settings during 2D search and the malleability of these settings might also account for results on the role of orientation-specificity in areas such as categorical search (e.g., Baier & Ansorge, 2019) or shape perception (cf. Biederman, 1987; Marr, 1982). Finally, our results also revealed a limitation of attentional guidance by shape. Even if participants searched for an equilateral triangle pointing in a specific direction, the attentional control setting was sensitive to all triangles with the same mirror symmetry axis as the target, even those pointing in the opposite direction. It might be that the pointing direction of a multistable figure like an equilateral triangle cannot be processed fast enough to act as a guiding feature. For the isosceles trapezoid, we found a small effect of the pointing direction (Experiment 6). The target-matching cue elicited a stronger validity effect than the cue pointing in the opposite direction (180°-rotated), although the validity effect of both cues was significantly above zero. However, this result might be different if participants have to search for a specific target orientation, which was not the case in Experiment 6.

Contingent capture versus visual search

Although a contingent-capture protocol can be useful to investigate attentional guidance, there are also some caveats. For example, it is impossible to say which processes occurred during the interval between cue and target without additional measures. It might be that cues eliciting no validity effect nevertheless attracted attention to some degree, and participants only successfully dismissed these stimuli as being too target-dissimilar by the time the targets had their onset (cf. Theeuwes et al., 2000; but see Theeuwes, 1992).

It is also possible that even in the cases where we found a validity effect, this validity effect reflected both – initial capture by the cue plus subsequent (but not completed) suppression of the cue. In future studies, some of these problems of the contingent-capture protocol could be remedied using electroencephalography to study in more detail and with higher temporal precision when attention is directed to the cue during the cue-target interval (cf. Eimer & Kiss, 2008; Luck & Hillyard, 1994). The problems can also be alleviated by varying the cue-target interval to see if an effect has already started or has come to an end for different cue-target intervals (cf. Gibson & Amelio, 2000; Remington et al., 2001; Schoeberl & Ansorge, 2019).

Another problem is that the non-singleton stimuli in the cueing display are not the same as the distractors in the target display. Thus, the testbed for the attentional effects of the distractors during visual search is not the same as that for the cues in the contingent-capture protocol. Although this can be an advantage (e.g., by reducing the effect of distractor-directed suppression strategies), it might sometimes be a disadvantage. For example, a higher similarity between singleton cue and cueing-display non-singletons could (unintentionally) diminish a validity effect, even where the same discrimination difficulty would not apply to target-distractor discrimination during visual search. However, the influence of varying similarity between cue and cueing displays' non-singletons could also be made a topic of control manipulations if necessary. If used as a complementary method for convergent conclusions, we see great potential in using the contingent-capture protocol for investigating attentional guidance by shapes.

In our view, the predominant usage of the contingent capture protocol to investigate search for colors and to demonstrate top-down over bottom-up influences on visual attention (see Büsel et al., 2020) has blocked its use as a toolbox for far more potential insights into the function of attentional control settings during visual search. In conclusion, the present research should also provide arguments for the usage of the contingent-capture protocol for more fine-grained and complementary insights into the workings of visual search settings in a broader range of research on visual attention.

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Appendix

Additional Tables With Results

Table A1

Mean Validity Effects for Each Target Shape and Cue Type in Experiment 3

Cue Type	*M* (*SD*)	95% CI	*t*(*df*)	*p*	d_{unb}	95% CI
Triangle Pointing Down						
matching	62 (22)	[50, 74]	11.17(14)	< .001	2.73	[1.70, 4.05]
reconfigured matching edges	64 (25)	[51, 78]	10.03(14)	< .001	2.45	[1.50, 3.65]
difference	−2 (23)	[−15, 10]	−0.39(14)	.70	−0.09	[−0.61, 0.41]
Triangle Pointing Up						
matching	49 (33)	[31, 67]	5.76(14)	< .001	1.41	[0.73, 2.22]
Reconfigured matching edges	57 (33)	[39, 75]	6.76(14)	< .001	1.65	[0.92, 2.55]
difference	−8 (28)	[−24, 7]	−1.12(14)	.28	−0.23	[−0.76, 0.27]
Square						
matching	32 (26)	[16, 47]	4.47(13)	.001	1.13	[0.49, 1.88]
non-matching edges (45° rotated [diamond])	−8 (19)	[−19, 2]	−1.66(13)	.12	−0.42	[−0.99, 0.11]
difference	40 (31)	[22, 58]	4.81(13)	< .001	1.67	[0.91, 2.61]
Diamond						
matching	13 (23)	[0, 25]	2.18(15)	.045	0.52	[0.01, 1.06]
non-matching edges (45° rotated [square])	11 (26)	[−3, 25]	1.73(15)	.10	0.41	[−0.09, 0.94]
difference	2 (40)	[−20, 23]	0.15(15)	.88	0.06	[−0.43, 0.55]

Note. Mean and *SD* (in parentheses) in ms. Contrasts: difference = validity effect difference between the two cue types listed above.

Table A2

Mean Validity Effects for Each Cue Type in Experiment 4

Cue Type	*M* (*SD*)	95% CI	*t*(*df*)	*p* [a]	d_{unb}	95% CI
matching	46 (28)	[34, 58]	7.76(21)	< .001	1.60	[1.00, 2.30]
reconfigured matching edges	61 (19)	[52, 69]	14.64(21)	< .001	3.01	[2.09, 4.14]
non-matching edges (45° rotated)	65 (21)	[55, 74]	14.56(21)	< .001	3.00	[2.08, 4.12]
non-matching edges (90° rotated)	63 (20)	[55, 72]	15.12(21)	< .001	3.11	[2.16, 4.27]
Contrasts						
matching vs. reconfigured matching edges	−14 (22) [b]	[−24, −5]	−3.16(21)	.023	−0.65	[−1.13, −0.20]
matching vs. non-matching edges (45° rotated)	−18 (24)	[−29, −8]	−3.64(21)	.015	−0.75	[−1.25, −0.29]
matching vs. non-matching edges (90° rotated)	−17 (23)	[−7, 16]	−3.51(21)	.015	−0.72	[−1.22, −0.27]
reconfigured matching edges vs. non-matching edges (45° rotated)	−4 (18)	[−12, 4]	−1.05(21)	.90	−0.22	[−0.64, 0.20]
reconfigured matching edges vs. non-matching edges (90° rotated)	−3 (10)	[−7, 2]	−1.26(21)	.82	−0.26	[−0.69, 0.16]
non-matching edges (45° rotated) vs. non-matching edges (90° rotated)	−1 (15) [b]	[−6, 8]	0.35(21)	1.00	0.07	[−0.34, 0.49]

Note. Mean and *SD* (in parentheses) in ms.

[a] Adjusted using the Benjamini-Yekutieli procedure (Benjamini & Yekutieli, 2001)

[b] These values deviate slightly from the difference between the rounded means since the latter contain rounding errors.

Achieved Statistical Power Estimation with Simulations

The achieved power of an experiment is essential to assess whether the results are robust and reproducible. Using simulations is a flexible way (and often the only one) to estimate the achieved power realistically. Therefore, we briefly discuss the advantages of this approach and present all information to reproduce our simulations.

Statistical Power

Statistical power refers to the ability of an experiment to find a significant effect provided there is one. Statistical power is not a feature of a statistical test but depends instead on the whole experiment. Factors influencing statistical power are the sample size, the size of the effect, and the chosen significance criterion. Additionally, low measurement reliability (i.e., low numbers of trials per condition), unbalanced research designs (i.e., substantially different numbers of trials in different conditions), and the distribution of the measured variable all influence power (cf. Brysbaert, 2019; Brysbaert & Stevens, 2018; O'Keefe, 2007). High power is especially important if an experiment yields non-significant results since otherwise, the power might have been just too low to find an effect. With high power, one would have most likely found an effect if there was one, and, therefore, non-significant results can be more confidently interpreted as the absence of an effect.

Often, the power of a statistical test is calculated based on the sample size, the significance criterion, and the effect size. However, this does not incorporate the design and measurement factors mentioned above and, therefore, might be quite different from the actual power of an experiment. To get a more realistic estimation of power, it is crucial to take the measurement reliability, the distribution of the measured variable, and the design into account, which can be done with a simulation after the data is collected. Furthermore, if an effect predicts more than one result (e.g., the contingent-capture hypothesis predicts a significant validity effect for matching cues and, at the same time, a reduced or even non-significant one for non-matching cues), a simulation allows checking for more than one result simultaneously.

A simulation allows us to repeat the experiment with similar measurement reliability and variance, the same number of analyzed trials per condition (taken unbalanced numbers into account), and the same sample size. The smallest effect of interest (20 ms) is simulated by adjusting the distribution from which the reaction times are randomly drawn for all experimental conditions. Thus, there is no need for a standardized effect size. Then the statistical tests are run for each simulation, and the proportion of simulations where the effect is found constitutes the power of the experiment.

It is essential not to use the effect size of the experiment for the power analysis since if the experiment is underpowered, the effect size might be overestimated (e.g., Albers & Lakens, 2018). Furthermore, the effect size of a non-significant test is a direct function of the *p* value and therefore not informative (Hoenig & Heisey, 2001). We normalized the reaction times for each participant and each experimental condition to remove individual reaction time differences and differences between the conditions without changing the reaction time distribution. Then we added the general mean to the normalized reaction times to get more realistic values. We randomly draw values from this reaction times with replacement to simulate the reaction times (bootstrapping). We implemented the validity effect by subtracting 20 ms from the drawn reaction time in the condition with a valid target and a matching cue.

To simulate the variance of our data, we added to the mean parameter of the distribution for each participant a random number drawn from a normal distribution. Additional to this individual variance, we added a random number drawn again from a normal distribution to implement a variance between the experimental conditions within each participant. Due to this procedure, our simulated data had a similar measurement precision and standard deviation of the validity effect as our real data. The number of drawn reaction times per condition matched the number of correct trials in the actual experiment since we only analyzed correct trials. After we simulated the data, we calculated the validity effect for matching and non-matching cues and tested it against zero using a two-sided one-sample *t* test – as in our actual experiments.

Measurement Precision

As described, the number of observations is a critical factor for the statistical power in repeated-measurement designs, since more observations yield more reliable estimates of the dependent variable, which increases the statistical power (Brysbaert, 2019). We report the reliability of our dependent measures using intraclass correlation coefficients (ICCs) as measures of reliability. We calculated the ICC1 and ICC2 (cf. Shrout & Fleiss, 1979) using the functions `ICC1.lme()` and `ICC2.lme()` from the R package *psychometric* (Fletcher, 2010). The ICC1 is the average correlation between the measurements, which is sensitive to mean reaction time differences between participants and, thus, a measure of absolute agreement. The ICC2, in contrast, ignores the differences between participants and, thus, represents the consistency of the measurement. We calculated both ICCs for the entire dataset and each experimental condition. Brysbaert (2019) recommends a minimum ICC2 of .80.

In Experiment 1, the ICC1 was .149, and the ICC2 was .988 for the entire dataset. The ICC1s per condition were .174, .125, .177, and .173 (*M* = .174). The ICC2s per condition were .927, .961, .929, and .974 (*M* = .927). In Experiment 2, the ICC1 was .122, and the ICC2 was .993 for the entire dataset. The ICC1s per condition were .131, .128, .128, and .142 (*M* = .131). The ICC2s per condition were .951, .982, .950, and .984 (*M* = .951). In Experiment 3, the ICC1 was .115, and the ICC2 was .992 for the entire dataset. The ICC1s per condition were .114, .115, .122, and .127 (*M* = .114). The ICC2s per condition were .941, .979, .946, and .982 (*M* = .941). In Experiment 4, the ICC1 was .185, and the ICC2 was .997 for the entire dataset. The ICC1s per condition were between .173 and .264 (*M* = .216). The ICC2s per condition were between .962 and .983 (*M* = .975). In Experiment 5, the ICC1 was .112, and the ICC2 was .994 for the entire dataset. The ICC1s per condition were between .087 and .147 (*M* = .121). The ICC2s per condition were between .906 and .970 (*M* = .944). In Experiment 6, the ICC1 was .084, and the ICC2 was .992 for the entire dataset. The ICC1s per condition were between .068 and .122 (*M* = .091). The ICC2s per condition were between .860 and .962 (*M* = .928). In Experiment 7, the ICC1 was .124, and the ICC2 was .995 for the entire dataset. The ICC1s per condition were between .107 and .219 (*M* = .151). The ICC2s per condition were between .942 and .972 (*M* = .960).