Orientation invariance in visual shape perception

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To assess directly the orientation-invariance of specific shape representation stages in humans, we examined whether rotation (on the image plane or in depth) modulates the conjunction and linear non-separability effects in a shape visual search task (M. Arguin & D. Saumier, 2000; D. Saumier & M. Arguin, 2003). A series of visual search experiments involving simple 2D or 3D shapes show that these target type effects are entirely resistant to both planar and depth rotations. It was found however, that resistance to depth rotation only occurred when the 3D shapes had a richly textured surface but not when they had a uniform surface, with shading as the only reliable depth cue. The results also indicate that both planar and depth rotations affected performance indexes not concerned with the target type effects (i.e. overall RTs and magnitude of display size and target presence effects). Overall, the present findings suggest that the shape representations subtending the conjunction and linear non-separability effects are invariant across both planar and depth rotations whereas other shape representation stages involved in the task are orientation-specific.

Keywords: shape representation, orientation invariance, visual search

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Introduction

Humans typically recognize three dimensional (3D) objects from various viewpoints or orientations with ease. While this ability is often taken for granted, it raises important theoretical issues regarding the mechanisms and representations that subserve visual object recognition. In particular, most objects can project an infinite variety of different images on the retina depending on their viewpoint. Theories must be able to explain how our visual system can map the novel retinal image of a familiar object to its stored visual knowledge in order to allow its recognition—i.e. shape constancy.

Two rival theoretical views have been proposed to account for shape constancy. One view, often referred to as a structural-description model, proposes that internal shape representations encode the 3D structure of objects in terms of a collection of volumetric primitives and their connectedness (Biederman, 1987; Biederman & Bar, 1999; Biederman & Gerhardstein, 1993; Marr, 1982; Marr & Nishihara, 1978; Peissig, Wasserman, Young, & Biederman, 2002; Pentland, 1985). The 3D shape properties that are shared across viewpoints of an object (i.e. the non-accidental properties, see Biederman, 1987) would be the basis for its recognition (Peissig et al., 2002). Thus, according to this view, as long as the non-accidental properties remain visible, shape representations should be orientation-invariant. An alternative view, referred to as image-based theory, suggests that shape representations exclusively code 2D information. This necessarily implies that representations are view-specific, and that the recognition of an object in a novel orientation requires a special process of alignment, normalization and/or interpolation to match it to its stored 2D representation (Tarr & Bülthoff, 1995; Tarr, Bülthoff, Zabinski, & Blanz, 1997; Tarr & Pinker, 1989, 1990, 1991; Tarr, Williams, Hayward, & Gauthier, 1998).

To assess whether visual shape representations are orientation-specific or orientation-invariant, most studies have assessed the effect of object rotation relative to a familiar orientation on direct measures of performance such as response times (RTs) and/or error rates (e.g. Biederman, 1987; Biederman & Bar, 1999; Biederman & Gerhardstein, 1993; Jolicoeur, 1985; Leek & Johnston, 2006; Peissig et al., 2002; Tarr & Bülthoff, 1995; Tarr et al., 1997; Tarr & Pinker, 1989, 1990, 1991; Tarr, Williams, et al., 1998). The logic underlying this direct approach rests on the assumption that each theory generates different predictions regarding the impact of rotation on performance. Thus, it is assumed that orientation-invariant representations must predict rotation-invariant performance, provided that the object's non-accidental properties remain visible. In contrast, because

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the normalization process is costly, the hypothesis of orientation-specific representations predicts a performance cost of rotation that is proportional to the distance between new and familiar orientations. The findings from studies assessing direct effects of rotation on performance range from null to very large rotation costs. These variable outcomes across experiments have largely been attributed to stimulus factors such as the nature of shape contrasts between stimuli (e.g. Biederman & Bar, 1999), the discriminability of these items (Hayward & Williams, 2000), the presence of polar features (Leek & Johnston, 2006), or the level of detail with which objects must be represented to perform a particular task (cf. view complexity; Tjan & Legge, 1998).

In addition to stimulus factors, the experimental approach used to measure rotation costs may also significantly impact the outcome. In particular, it is possible that the direct measurement of performance costs as a function of rotation may not offer an entirely valid picture of the coding scheme underlying visual shape representation (Stankiewicz, 2002). Indeed, against the assumptions upon which the direct approach is based, there are some structural-description theories that predict rotation-dependent performance (Hummel & Biederman, 1992; Hummel & Stankiewicz, 1996). In contrast, other theories assume image-based representations but predict rotation-invariant performance (Seibert & Waxman, 1989). Another problem with the direct approach is the difficulty of dissociating rotation effects that are simply attributable to the altered stimulus information that follows rotation from effects that are truly due to how the information is processed (Liu, Kersten, & Knill, 1999; Tjan & Legge, 1998). Considered this way, demonstrations of rotation costs may become suspect with regards to their interpretation value for visual shape processing since the effect may be attributable to the large changes in stimulus information across rotations. Conversely, observations suggesting no rotation cost may also be ambiguous if there is doubt as to the strength of the manipulation of stimulus rotation. We will return to this issue in the General discussion.

Relatedly, it has been suggested that, even assuming high-level orientation-invariant representations, the early stages of visual processing may be orientation-specific (Bar, 2001). According to this proposal, since we have more experience with some orientations or viewpoints than others, the neural paths leading to object recognition in these particular orientations are more sensitive and therefore lead to faster recognition. For example, one object in two different views possesses different sets of visible features (e.g. the lines defining a chair in two different views are oriented differently, some features may be occluded in one view and visible in another, etc.) and therefore activates different neural paths in early processing. Despite the fact that, in the end, both neural paths might activate the same orientation-invariant shape representation, the higher sensitivity of the early neural path activated by a familiar viewpoint will lead to faster, more effective high-level processing and performance than an unfamiliar viewpoint.

The above discussion argues that the direct approach cannot determine unequivocally the orientation-specificity or invariance of shape representations. For this purpose, we propose an alternative experimental approach based on second-order effects of stimulus rotation. The specific question to be assessed in this approach is whether stimulus rotation modulates (i.e. interacts with) perceptual effects assumed to characterize the representation obtained at some stage of shape processing, independently of the orientation-specificity or invariance of other stages involved in performing the task.

As an illustration, assume that a particular stimulus factor, say shape complexity, affects perceptual performance through its impact on a particular stage for shape perception, say contour extraction. To determine whether this putative "contour extraction" stage is orientation-specific or invariant, the second-order approach will examine the impact of shape complexity as a function of stimulus rotation. If the results demonstrate such a modulation, then it should be concluded that the processing stage affected by shape complexity is orientation-specific. For instance, one might find a greater cost of shape complexity with than without stimulus rotation, which could indicate that contour extraction is less effective with rotated stimuli, thereby making it more susceptible to the effect of shape complexity. Conversely, findings might indicate that the effect of shape complexity is unaffected by stimulus rotation. This would suggest that the contour extraction stage is orientation-invariant, i.e. what it does or how it does it is unchanged by rotation. Importantly, the latter outcome is possible even if stimulus rotation has a direct (main) effect on the performances measured, which would indicate that some processing stage involved in the task, other than contour extraction, is orientation-specific.

In the investigation reported here, we aim to apply the second-order approach described above to examine the orientation-specificity of particular processing stages involved in shape perception. Specifically, we examined how stimulus rotation modulates two perceptual effects previously documented in our laboratory, and which index what we believe to be important processes in human visual shape perception.

One of the effects examined is the shape conjunction effect in the visual search task. It is characterized by a marked decrease in search rates when the target is made of a combination of the shape features of the distractors, as opposed to when the target is defined by a unique feature (Arguin & Saumier, 2000; Saumier & Arguin, 2003; Treisman & Sato, 1990). For instance, with simple ellipsoids that are allowed to vary only according to their elongation and curvature (Figure 1), a conjunction target would share its elongation with a subset of distractors and its curvature with others (e.g. in Figure 1, the target is the

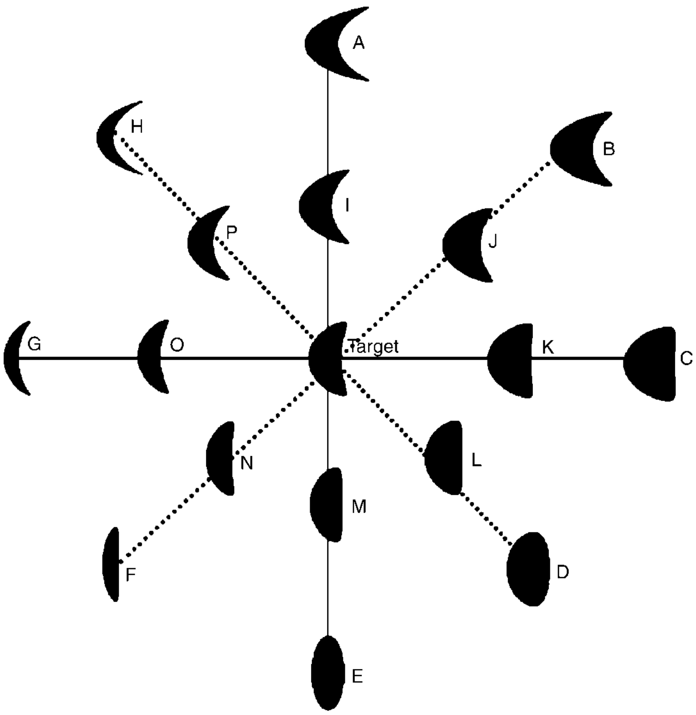

Figure 1. 2D stimuli used in the experiment of Saumier and Arguin (2003) and in Experiment 1 of the present report. Each blob location corresponds to its location in a shape space composed of the dimensions of elongation (horizontal axis) and curvature (vertical axis).

item labeled "Target" and the distractors are the shapes labeled A and G). In contrast, a target defined by a unique feature (baseline condition) has an elongation or curvature not shared with distractors (and which is linearly separable from distractor features; see next—e.g. in Figure 1, the distractors would be the shapes labeled D and F). The other effect is that of linear non-separability, which involves a marked decrease in search rates when the unique feature(s) defining the target is (are) not linearly separable from the features of the distractors, as opposed to when they are (such as in the baseline condition described above; Arguin & Saumier, 2000; Saumier & Arguin, 2003). For example, if the elongation and the curvature of the target are midway between the elongation and the curvature of each distractor (e.g. distractors labeled D and H in Figure 1), then the target is not linearly separable from the distractors.

Arguin and Saumier (2000) and Saumier and Arguin (2003) reported conjunction and linear non-separability effects for combinations of shape features using 2D ellipsoid shapes that varied on the global dimensions of aspect ratio, curvature, and tapering (see also Arguin, Bub, & Dudek, 1996; for relevant data from a brain-damaged participant). These findings were obtained while the discriminability of the target from individual distractors was matched between the baseline and the conjunction or linear non-separability conditions. Thus, the effects are not an artifact of uncontrolled target-disctractor discriminability. Another relevant finding is that the conjunction and linear non-separability effects are differently affected by the factor of Target-distractor similarity. Thus, the results of Saumier and Arguin (2003) indicate that similarity had a greater impact on the linear non-separability effect than on the conjunction effect. This suggests that these effects are subtended by different mechanisms (see Saumier & Arguin, 2003; for details regarding this interpretation).

The observation of conjunction and linear non-separability effects when the stimuli were manipulated along the dimensions of aspect ratio, curvature, and tapering suggests that these are strongly correlated with the psychological dimensions by which shape is represented in the human visual system. Had this not been the case, the conjunction and linearly non-separable targets would have differed from distractors on a unique linearly separable feature (in terms of the representation obtained by the visual system) and the conjunction and linear non-separability effects would not have occurred (see Arguin et al., 1996 and Arguin & Saumier, 2000; for a more detailed discussion of this issue). Congruently, other researchers have also proposed empirical evidence and/or a theoretical basis for the psychological validity of these dimensions (e.g. Barr, 1981; Biederman, 1987; Brooks, 1981; Marr, 1982; Marr & Nishihara, 1978; Pentland, 1985; Stankiewicz, 2002). The observation of a conjunction effect for shape features also argues for distributed shape representations, in which a stimulus is defined through a collection of discrete features, each characterizing the item on a particular dimension. The logic subtending this position is similar to that proposed by Treisman's feature integration theory (e.g. Treisman & Gelade, 1980). Specifically, the occurrence of a conjunction cost in a visual search task signals that the features shared between the target and distractors are coded separately and that their integration involves an additional processing step that is signaled by a performance cost when this integration is obligatory relative to when it is not (see also Eckstein, 1998; for relevant observations and discussion). The linear non-separability effect on the other hand, indicates the existence of a discrimination mechanism that allows the rapid and automatic detection of the target if a unique straight line can separate the representations of the target and distractors in the relevant feature space (see Bauer, Jolicoeur, & Cowan, 1996a, 1996b, 1998, 1999; D'Zmura, 1991; for related observations in the color domain and Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992; in the orientation domain). When the target does not obey this rule, then a different, less effective discrimination mechanism must be involved. The reader is referred to Arguin and Saumier (2000) and to Saumier and Arguin (2003) for a more detailed discussion of these effects.

If the representations subtending the conjunction and linear non-separability effects are orientation-specific, then we should expect these effects to be significantly altered or even eliminated if the target and distractors in a visual search task are displayed in mismatching orientations. Indeed, rotation modifies the local image features defining a shape: a planar rotation modifies their orientation and a depth rotation modifies their 2D appearance, for example, by increasing or decreasing the curvature or the elongation of the 2D projection of the object. Orientation-specific representations imply that the orientation of visual features is intrinsic to the representation. Hence, planar or depth rotations will result in distinct representations for each orientation of a particular shape. Within the present context, this view implies that if the target and distractors are shown in different orientations, then even if the target is objectively (i.e. in its 3D instantiation) a conjunction of distractor features or linearly not separable from distractors, its internal representation will not obey these constraints—hence the prediction of a reduction or loss of these effects. In contrast, orientation-invariant representations should lead to conjunction and linear non-separability effects that are resistant to stimulus rotation (planar or in depth) since orientation is not an intrinsic property of the representation. The experiments reported below will assess these predictions.

In the present study, the modulation of the conjunction and linear non-separability effects according to image plane or depth rotation was examined in visual search tasks using the 2D stimuli of Saumier and Arguin (2003; Figure 1) or 3D versions of these 2D patterns (see Figure 4). Since the participants were unfamiliar with the stimuli used, they were not expected to possess representations of the items prior to the experiment. All the orientations and viewpoints chosen were presented to the subjects an equal number of times, and therefore had the same degree of familiarity. Thus, according to a theoretical framework assuming orientation-specific representations, our participants should develop one shape representation for each orientation or viewpoint presented during the course of the experiments (see description of image-based theory, above). This means that target detection should not require any process of alignment, normalization or interpolation to some canonical representation since all possible instances of the target are equally well represented. Experiments 1 and 4 evaluated the impact of image plane rotations on the conjunction and linear non-separability effects, and Experiments 2, 3, 5, and 6 assessed the effect of depth rotation.

Experiment 1

The aim of Experiment 1 was to examine the impact of image plane rotations on the magnitude of the conjunction and linear non-separability effects previously demonstrated by Arguin and Saumier (2000) and Saumier and Arguin (2003) in the shape domain.

The visual search task was largely similar to that reported by Saumier and Arguin (2003) and the shape relation between the target and distractors was one of three types: 1—The target possessed a unique shape property that was linearly separable from those of the distractors (single-feature, linearly separable; 1D-LS; Figure 2A). This constitutes the baseline condition against which the conjunction and linear non-separability effects will be assessed. 2—The target was a conjunction of the shape properties of distractors (conjunction; CONJ; Figure 2B). 3—The target was a linear combination thereof (linear non-separability; LNS; Figures 2C and 2D). Two kinds of linear non-separability conditions were used. In the LNS(o) condition (Figure 2C), distractors mutually differed on two shape dimensions (i.e. curvature and elongation) and, in the LNS(p) condition (Figure 2D), distractors mutually differed on only one shape dimension (i.e. curvature or elongation only).

Most significantly, the discriminability of the target from individual distractors was matched across conditions based on the performances measured in a matching task. Specifically, the correct RTs and error rates on trials where the target was presented along with one particular distractor did not differ significantly across the 1D-LS, CONJ, LNS(o) and LNS(p) target types. The importance of this feature of the experimental design is that any performance difference across target types will be attributable to the particular shape relation entertained between the target and the distractor shapes displayed with it, and not to a mismatch across conditions on the discriminability of the target with individual distractors. Since the same shapes (in their 2D or 3D instantiations) were used across all the experiments reported here, this claim applies to all the target type effects that will be reported.

The results of Saumier and Arguin (2003) showed that the conjunction and linear non-separability effects were differently affected by the factor of Target-distractor similarity. Thus, similarity had a greater impact on the linear non-separability effect than on the conjunction effect, which suggests that these effects are subtended by different mechanisms. The present experiment was a replication of the experiment conducted by Saumier and Arguin (2003), but this time using stimuli displayed in fixed vs. variable orientations on the image plane. With a fixed orientation, all stimuli had their major axis oriented vertically. With variable orientations, each item displayed had its orientation determined randomly and independently of the others.

Method

Participants

Eight students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the experiment and all had normal or corrected acuity.

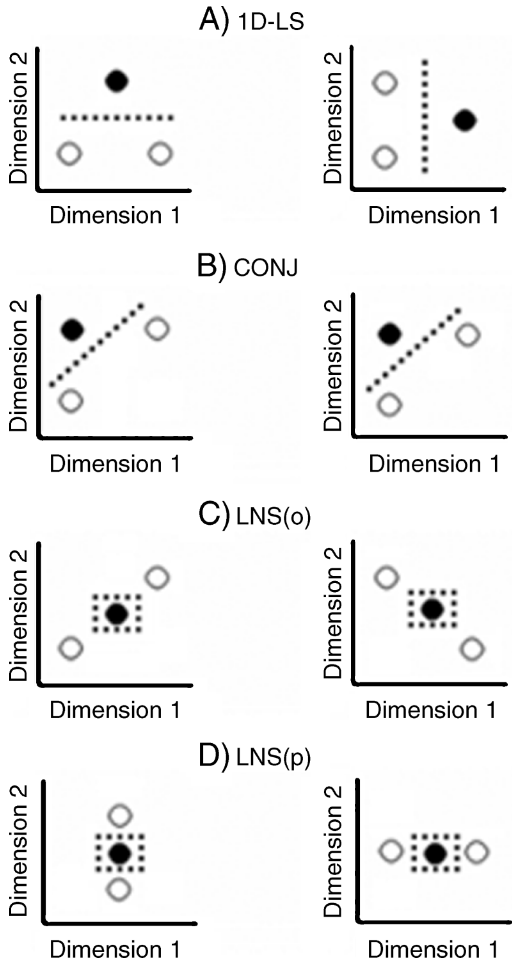

Figure 2. Relative locations of the target and distractors in shape space for the different Target types used in the present study. The target is represented by a filled circle and the distractors by empty circles. The dashed lines indicate the boundary that separates the target form its distractors in shape space, which is assumed to serve as the basis for discriminating the target from its distractors. (A) The target in the 1D-LS condition is linearly separable from its distractors and possesses a unique shape property, i.e. not shared with distractors. (B) The target in the CONJ condition is linearly separable from its distractors but is made of a conjunction of distractor properties. (C) The target in the LNS(o) condition is not linearly separable from its distractors and is made of a linear combination of the features defining the distractors. Distractors mutually differ on two shape dimensions. (D) The target in the LNS(p) condition is not linearly separable from the distractors and is made of a linear combination of the features defining the distractors. Distractors mutually differ on only one shape dimension.

Stimuli

The stimuli were the same as those used by Saumier and Arguin (2003). The shapes were generated by parametric deformations of a 2D ellipse on the dimensions of elongation (ratio of the length of the major axis over that of the minor axis) and curvature of the major axis (see Arguin et al., 1996 for additional details regarding the generation of the stimuli). The length of the major axis of all shapes was normalized to 3.0 cm (1.8 degrees of visual angle at the viewing distance of 95 cm), whereas the length of the minor axis varied as a function of the dimension of elongation for each stimuli (see Saumier & Arguin, 2003 for details regarding the procedure used to determine the degree of curvature and elongation attributed to each shape).

The present experiment used a total of 16 distractors and one target. For each level of the target type factor (i.e. 1D-LS, CONJ, LNS(o) and LNS(p)), four sets of two distractors were used (see Table 1 and Figures 1 and 2). Among these sets, there were two with a high and two others with a low target-distractor similarity. Thus, the properties of the distractors included in each set were determined by a particular combination of target type and target-distractor similarity. Target-distractor discriminability was matched across target types (see above) separately for low and high similarity distractor sets.

The stimuli were displayed in either fixed or random orientations. The fixed- and random-orientation conditions were presented in separate blocks. In the random-orientation condition, the stimuli were presented in one of eight possible orientations, each separated by rotations of 45 degrees in the image plane. The orientation of each individual stimulus was determined randomly and independently. In the fixed-orientation condition, all stimuli were displayed at the same orientation, as displayed in Figure 1.

The stimuli were presented on a 17-inch DELL monitor of 1024 × 768 pixels resolution. The progress of the experiment and registration of the observer's performance were controlled by the PsychLab software.

Procedure

One block of 256 trials was created for each target-distractor set for a total of 32 blocks (i.e. four target types × two similarity levels × two orientation levels). The trials in each block were defined by a combination of two factors: display size (four levels: 3, 5, 7, or 9 items) and target presence (two levels: present or absent). These combinations were distributed randomly and occurred

	Distractor sets			
	Similar		Dissimilar	
Target type	Set 1	Set 2	Set 1	Set 2
1D-LS	N & L	P & N	D & F	F & H
CONJ	K & M	I & O	C & E	A & G
LNS(p)	J & N	L & P	B & F	D & H
LNS(o)	K & O	I & M	C & G	A & E

Table 1. List of distractor sets for each target-distractor condition in Experiment 1.

equally often in each block of trials. On positive trials, the two possible distractor shapes were presented an equal number of times. In order to maintain a constant number of items across positive and negative trials, there was one more instance of a distractor than of the other on negative trials. On these trials, the total number of exemplars of each distractor within each block was equal. Each participant completed all blocks (one block for each target-distractor set). The order of the blocks was determined randomly.

Each trial began with a fixation point (plus sign, Arial 24 points) displayed at the center of the screen for 500 ms. It was immediately followed by the search array, which remained on the screen until the subject responded. The stimuli were randomly presented at one of 12 locations, equally spaced on the perimeter of an imaginary circle subtending a diameter of 10.2 degrees of visual angle (17 cm at a distance of 95 cm) and centered on the fixation point.

Participants answered as fast and as accurately as possible with their left or right hand by pressing on the left or right button of a response box to indicate the presence or absence of the target. The buttons attributed to the response « target present » or « target absent » were counterbalanced across participants.

Results

As noted above, one factor that was manipulated in Experiment 1 is the visual similarity between the target and distractors. This manipulation was conducted in a spirit of replication, but, in the interest of succinctness, we chose here to not detail the results that specifically pertain to this factor. Indeed, they are not particularly relevant to the purpose of this article and target-distractor similarity did not interact with stimulus orientation in any way. Most importantly, it had no impact on the orientation × target type × display size interaction, which is of critical interest here. Not reporting the results regarding target-distractor similarity considerably shortens the present Results section as well as the Discussion that follows. To summarize however, we replicated the results of Saumier and Arguin (2003): the magnitude of the linear non-separability effect was magnified to a greater degree by increased target-distractor similarity than the conjunction effect. For this reason, only the dissimilar target-distractor sets will be used in the following experiments. Also, for the present experiment, the following description of the results will be restricted to conditions with dissimilar target-distractor sets.

Response times (RTs) that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 315 data points for the complete experiment (1.2% of trials). The error trials were also excluded from the RTs analyses. Error rates were not analyzed since they were quite low (2.7% overall). The data showed no speed-accuracy trade-off since the correlation between correct RTs and error rates was +0.97 ($p < .05$).

Figure 3 displays the average correct RTs as a function of display size for each target type and each orientation condition. Table 2 presents the results of the linear regression analyses of RTs as a function of display size in all conditions.

Linear regression analyses of RT as a function of display size for each condition show that the display size effect is linear in all conditions. The ratios of positive to negative slopes of RTs as a function of display size approximate 0.5, which is congruent with a serial self-terminating strategy. In all relevant instances, the slopes are greater in both LNS conditions than in the 1D-LS condition, which is congruent with a linear non-separability effect.

A four-way within-subject ANOVA including the factors of target type (1D-LS, CONJ, LNS(o) and LNS (p)), orientation (fixed or random), target presence (present or absent) and display size (3, 5, 7, or 9 items) was carried out on correct RTs. Main effects of target type [$F(3, 21) = 21.1$, $p < .001$], orientation [$F(1, 7) = 6.6$, $p < .05$], target presence [$F(1, 7) = 20.7$, $p < .005$] and display size [$F(3, 21) = 73.0$, $p < .001$] were obtained. These indicated a significant variation of RTs as a function of target type and shorter RTs with fixed than random orientations, as well as when the target was present than when it was absent. Finally, RTs increased regularly as a function of the number of items.

The two-way interaction of target type × display size was significant [$F(9, 63) = 15.8$, $p < .001$]. This result indicates that the search rate indexed by the display size effect was affected by target type. In order to determine the presence of the conjunction and linear non-separability effects, planned pairwise comparisons between the baseline 1D-LS condition and the CONJ, LNS(o) and LNS(p) conditions on the effect of display size were carried out. The results show a significantly faster search rate in the 1D-LS condition than in the CONJ [$F(3, 21) = 10.6$, $p < .001$], LNS(p) [$F(3, 21) = 7.9$, $p < .001$] and LNS(o) conditions [$F(3, 21) = 12.3$, $p < .001$], therefore indicating the presence of the conjunction and linear non-separability effects. In the main ANOVA, the interaction of target type × display size was qualified by a significant interaction of target type × display size × target presence [$F(9, 63) = 6.2$, $p < .001$]. As can be seen in Figure 3 and Table 2, this modulation of the target type effect on display size as a function of target presence is simply based on the fact that the effect is greater on target-absent than target-present trials. Relatedly, the effect of target type on RTs was also magnified on target-absent relative to target-present trials ([$F(3, 21) = 4.8$, $p < .01$].

Target presence also significantly modulated the effect of display size such that the latter was magnified when the

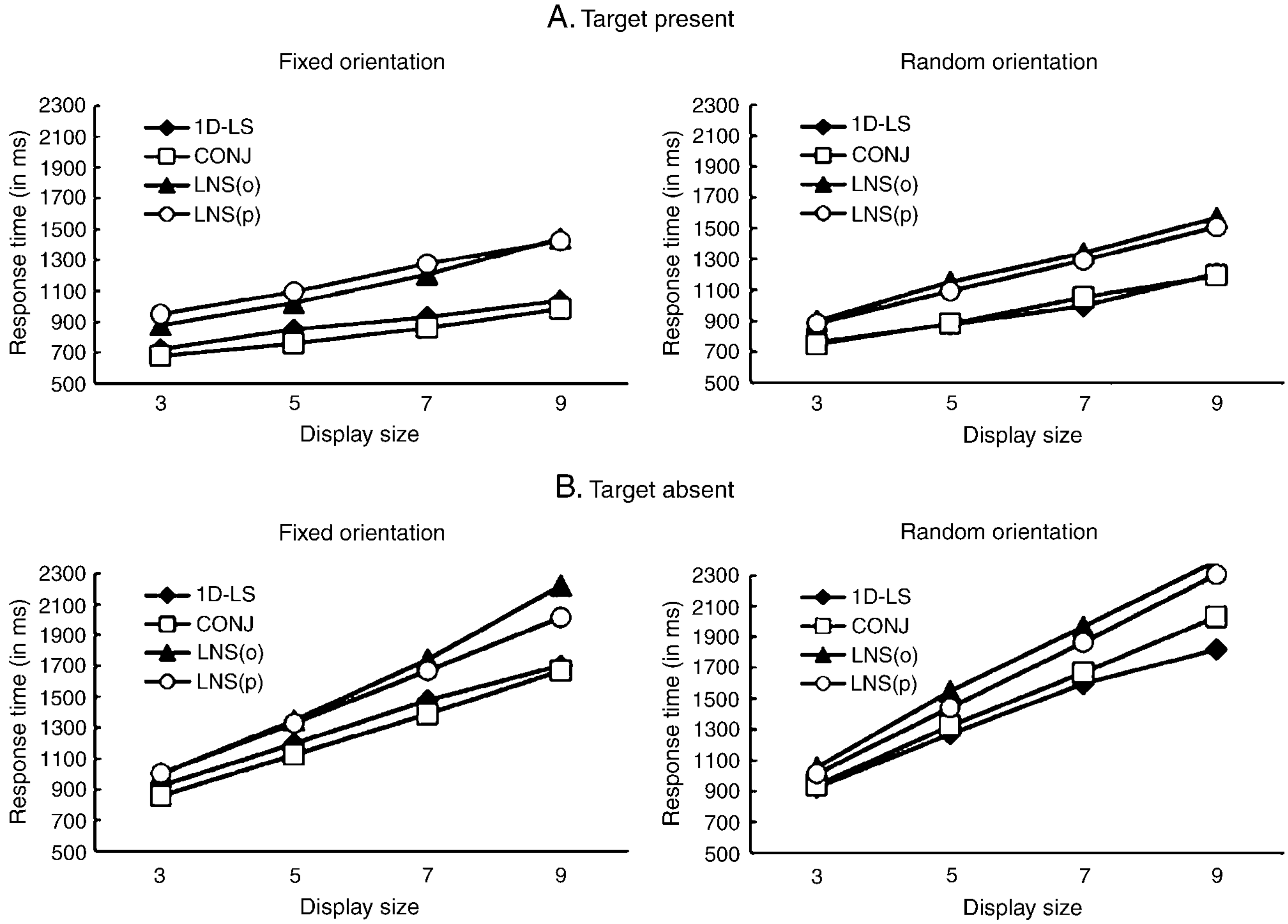

Figure 3. Average RTs in Experiment 1 as a function of display size for each target type and orientation condition on positive (A) and negative (B) trials.

target was absent relative to when it was present [$F(3, 21) = 31.3$, $p < .001$].

Of notable interest, the orientation factor had an impact on performances, as shown by the significant main effect of orientation noted above as well as the two-way interaction of orientation × display size [$F(3, 21) = 12.6$, $p < .001$], and the three-way interaction of target orientation × presence × display size [$F(3, 21) = 6.2$, $p < .005$]. The three-way interaction was followed-up by planned pairwise comparisons contrasting the display size effects across the fixed and random orientations separately for positive and negative trials. The display size effect was greater in the random than in the fixed orientation condition on both negative [$F(3, 21) = 10.3$, $p < .001$] and positive trials [$F(3, 21) = 19.4$, $p < .001$]. In both cases, the slopes of RTs as a function of display size are about doubled in the random vs. fixed orientation conditions (ratios are of 2.1 on both target-present and

		Positive trials			Negative trials			
Condition		Intercept (ms)	Slope (ms/item)	R^2	Intercept (ms)	Slope (ms/item)	R^2	Pos/neg ratio
Fixed orientation	1D-LS	519.1	9.1	0.89	497.5	22.8	0.97	0.40
	CONJ	489.6	20.4	0.96	464.9	51.6	0.99	0.39
	LNS(o)	559.2	33.3	0.99	493.1	68.8	0.99	0.42
	LNS(p)	541.0	23.2	0.99	487.6	55.2	0.99	0.48
Random orientation	1D-LS	491.8	28.0	0.99	512.8	52.2	0.99	0.54
	CONJ	516.5	35.2	0.99	402.2	100.7	0.99	0.35
	LNS(o)	569.6	54.5	0.99	409.6	127.5	0.99	0.36
	LNS(p)	570.6	42.4	0.99	404.5	116.3	0.99	0.43

Table 2. Linear regressions of correct RTs in each condition of Experiment 1 with dissimilar target-distractor sets.

absent trials). Of greatest importance in the present context is the non-significant three-way interaction of target type × display size × orientation [$F(9, 63) < 1$] in the main ANOVA. This result indicates that having stimuli in a fixed orientation or in random orientations had no impact on the modulation of search rates by target type. In other words, the present results indicate substantial conjunction and linear non-separability effects that are invariant to the rotation of the stimuli on the picture plane.

Discussion

The results of the present experiment replicate the demonstration of the conjunction and linear non-separability effects previously shown by Arguin and Saumier (2000) and Saumier and Arguin (2003). Thus, search rates are slower if the target is made of a conjunction of distractor features (CONJ) or if it is not linearly separable from distractors (LNS(o) and LNS(p)) than if it differs from distractors by a single, linearly separable feature (1D-LS).

Most importantly, the present results show that the pattern of findings pertaining to the conjunction and the linear non-separability effects was unaffected by whether stimuli were displayed in a fixed or random orientations. It must be emphasized however, that the manipulation of stimulus orientation was strong enough to produce an impact on performances, which is indicated by the main effect of orientation as well as the significant interactions involving the factor of orientation. Notably, the search rates were about twice as fast with a fixed orientation compared to random orientations. Therefore, the results of Experiment 1 support the conjecture that the observation of a cost of stimulus rotation on performance does not necessarily imply orientation-specific shape representations for all the processing stages involved in a particular task. Indeed, the shape representations indexed by the conjunction and linear non-separability effects are unaffected by the manipulation of stimulus orientation applied in this experiment. Thus, it must be concluded that the shape representations upon which they are based are not sensitive to image-plane rotations and that stimulus rotation affected processing stages other than those indexed by the conjunction and linear non-separability effects. We will return to this latter issue in the General discussion.

Experiment 2

The goal of Experiment 2 was to test whether the conjunction and linear non-separability effects in the shape domain (Arguin & Saumier; 2000; Saumier & Arguin, 2003) also occur with 3D shapes, i.e. shapes that have a 3D aspect. For this purpose, the shapes used for the

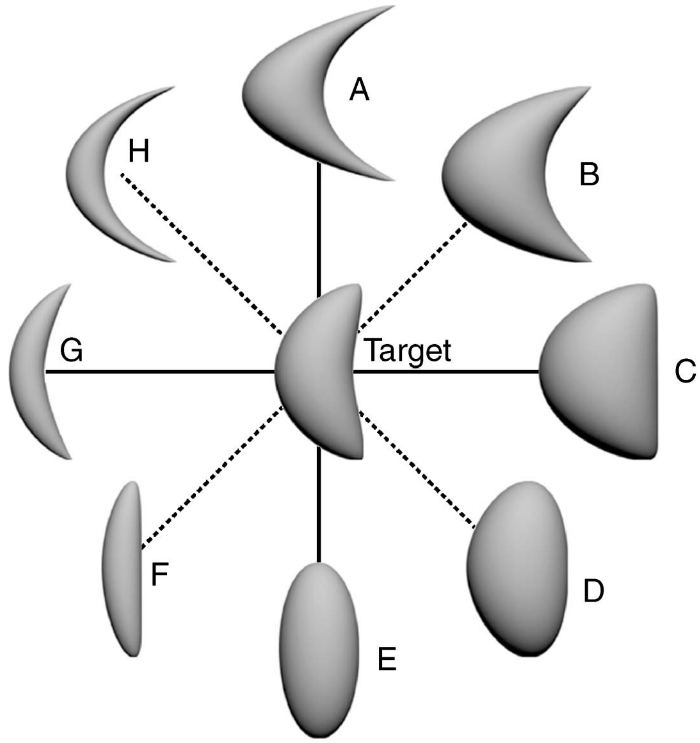

Figure 4. 3D stimuli used in Experiment 2. Each stimulus is located in a shape space of elongation (horizontal axis) and curvature (vertical axis). See text for details.

dissimilar target-distractor sets in Saumier and Arguin (2003) and in Experiment 1 were reproduced using a 3D drawing program that offered a depth dimension to the stimuli through surface shading (Figure 4). The reason for using the dissimilar target-distractor sets only is that they appear to be more sensitive to the conjunction effect, which is suggested by the regression slopes of Saumier and Arguin (2003) as well as those of Experiment 1. In addition, only one type of linearly non-separable target-distractor configuration was used, which corresponds to the LNS(o) of Experiment 1—where distractors differ mutually on elongation and curvature. Given a replication of the conjunction and linear non-separability effects with 3D stimuli in Experiment 2, a subsequent experiment (Experiment 3) will assess whether these effects resist the impact of depth rotation of the stimuli.

Method

Participants

Twelve students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the experiment and all had normal or corrected acuity.

Stimuli

Stimuli were 3D versions of the shapes used by Saumier and Arguin (2003) in their dissimilar target-distractor sets,

Target type	Distractor sets Set 1	Set 2
1D-LS	D & F	F & H
CONJ	A & G	C & E
LNS	B & F	D & H

Table 3. List of distractor sets for each target type condition in Experiments 2 and 3.

which were produced using the ElectrikImage Universe software. Their size was the same as the stimuli used in Experiment 1.

The present experiment included eight distractors and one target which are displayed in Figure 4. For each target type (i.e. 1D-LS, CONJ and LNS), two sets of distractors were used. The complete list of stimulus sets is provided in Table 3. The shape relations between the target and distractors that defined each target type are the same as described in the Introduction and used in Experiment 1.

The stimuli were presented on a 17-inch DELL screen of 1024 × 768 pixels of resolution. The progress of the experiment and registration of the observer's performance were controlled by the E-Prime software (Psychology Software Tools, Pittsburgh, PA, 2002).

Procedure

One block of 160 trials was created for each target-distractor set. Therefore, six blocks were created (i.e. two sets for each of three target types). The trials in each block were composed of a combination of two factors: display size (four levels: 3, 5, 7, or 9 items) and target presence (two levels: present or absent). Each combination occurred with an equal frequency and trials were ordered randomly. The rest of the procedure was the same as in Experiment 1.

Results

RTs that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 315 data points for the complete experiment (2.7% of trials). The error trials were also excluded from the RTs analyses. Error rates were not analyzed since they were quite low (3.4% overall). The data showed no speed-accuracy trade-off since the correlation between correct RTs and error rates was 0.06 (ns).

Figure 5 displays the average correct RTs as a function of display size for each target type on positive and negative trials. Table 4 displays the results of the linear regression analyses of RTs as a function of display size in all conditions.

Linear regression analyses of RTs as a function of display size for each target type showed that the display size effect is linear in all conditions. Except for the LNS condition where the ratio of positive over negative slopes is near 0.75, all other ratios approximate 0.5, which is congruent with a serial self-terminating strategy. The slopes of reaction times are greater in the LNS and CONJ conditions than in the 1D-LS condition, which is congruent with the presence of linear non-separability and conjunction effects.

A three-way within-subject ANOVA including the factors of target type (1D-LS, CONJ, LNS), target presence (present or absent) and display size (3, 5, 7 or 9 items) on the dependent variable of correct RTs was carried out. Main effects of target type [$F(2, 10) = 51.2$, $p < .001$], target presence [$F(1, 11) = 40.2$, $p < .001$], and display size [$F(3, 9) = 40.5$, $p < .001$] were obtained. These indicated a significant variation of RTs as a function of target type, shorter RTs when the target was present than when it was absent, and a linear increase of RTs as a function of the number of items as shown by the regression analyses (Table 4).

All pairwise interactions as well as the target type × display size × target presence [$F(6, 66) = 7.4$, $p < .01$] were significant (all p's $< .01$). A breakdown of the

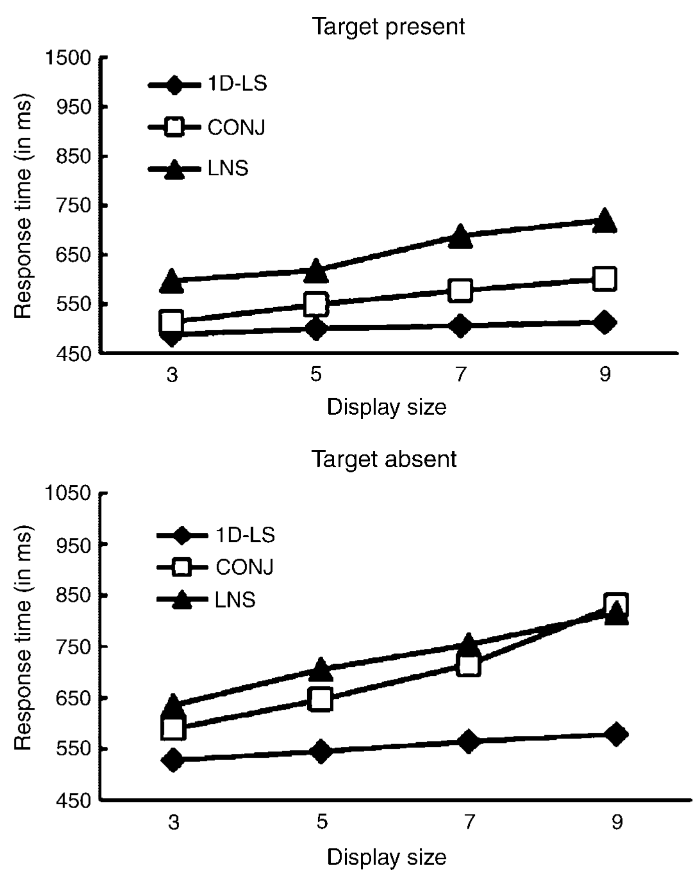

Figure 5. Average RTs in Experiment 2 as a function of display size for each target type on positive and negative trials.

Condition	Positive trials: Intercept (ms)	Positive trials: Slope (ms/item)	Positive trials: R^2	Negative trials: Intercept (ms)	Negative trials: Slope (ms/item)	Negative trials: R^2	Pos/neg ratio
1D-LS	479.4	8.2	0.97	510.1	17.1	0.99	0.48
CONJ	486.3	28.8	0.99	495.7	79.3	0.97	0.36
LNS	545.0	43.9	0.96	579.1	58.9	0.99	0.75

Table 4. Linear regressions of correct RT for each condition in Experiment 2.

three-way interaction was conducted to verify the occurrence of the conjunction and linear non-separability effects separately for positive and negative trials. On positive trials, the display size effect was weaker in the 1D-LS condition than in either the CONJ [$F(3, 33) = 8.7$, $p < .01$] or the LNS [$F(3, 33) = 31.4$, $p < .001$] conditions, thereby confirming the conjunction and linear non-separability effects. These effects are confirmed for negative trials as well, with a weaker display size effect in the 1D-LS condition than in either the CONJ [$F(3, 33) = 22.4$, $p < .01$] or the LNS [$F(3, 33) = 10.4$, $p < .01$] conditions.

Discussion

The aim of this experiment was to verify that the conjunction and linear non-separability effects found with 2D blobs by Arguin and Saumier (2000), Saumier and Arguin (2003) and in Experiment 1 could be obtained with blobs having a 3D aspect. This is confirmed by the fact that the display size effect in Experiment 2 was significantly larger in the CONJ and LNS conditions than in the 1D-LS condition. This demonstration is essential since it shows that the 3D blobs can be used in visual search tasks to verify that the conjunction and linear non-separability effects are resistant to depth rotation. This is the purpose of Experiment 3.

Experiment 3

The aim of Experiment 3 was to examine the impact of the depth rotation of stimuli on the conjunction and linear non-separability effects with the 3D stimuli of Experiment 2. The predictions to be tested are the same as in Experiment 1 except that they pertain to depth instead of planar rotations. If the shape representation code underlying the conjunction and linear non-separability effects is sensitive to depth rotation (i.e. orientation-specific), then this manipulation will alter the target-distractor feature relations in the CONJ and LNS conditions such that they no longer obey the definition of these conditions (see Introduction for a detailed explanation). Thus, an elimination of conjunction and linear non-separability effects when stimuli are displayed in random orientations would be expected under the assumption of orientation-specific representations. In contrast, the resistance of these effects to depth rotation would be possible if the shape representations that mediate the conjunction and linear non-separability effects are orientation-invariant. Experiment 3 replicated the design and procedure of Experiment 2 except that the target and distractors were displayed in one of four different depth orientations selected at random.

Method

Participants

Twelve students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the study and all had normal or corrected acuity.

Stimuli

The materials and stimuli were the same as in Experiment 2. However, for the present experiment, the 3D shapes were presented in four different depth orientations: (1) zero degree of rotation (i.e. same orientation as in Experiment 2), (2) rotation of 35 degrees around the X axis and of 35 degrees around the Y axis, (3) rotation of 35 degrees around the X axis and of 35 degrees around the Z axis (4) rotation of 35 degrees around the Y axis and of 35 degrees around the Z axis (see Figure 6).

Procedure

The procedure was the same as in Experiment 2. However, on each trial, the orientation of each of the stimuli was determined randomly and independently. Within one block, each shape appeared an equal number of times at each orientation.

Results

RTs that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 192 data points for the complete experiment (1.7% of trials). The error trials were also excluded from the RTs analyses.

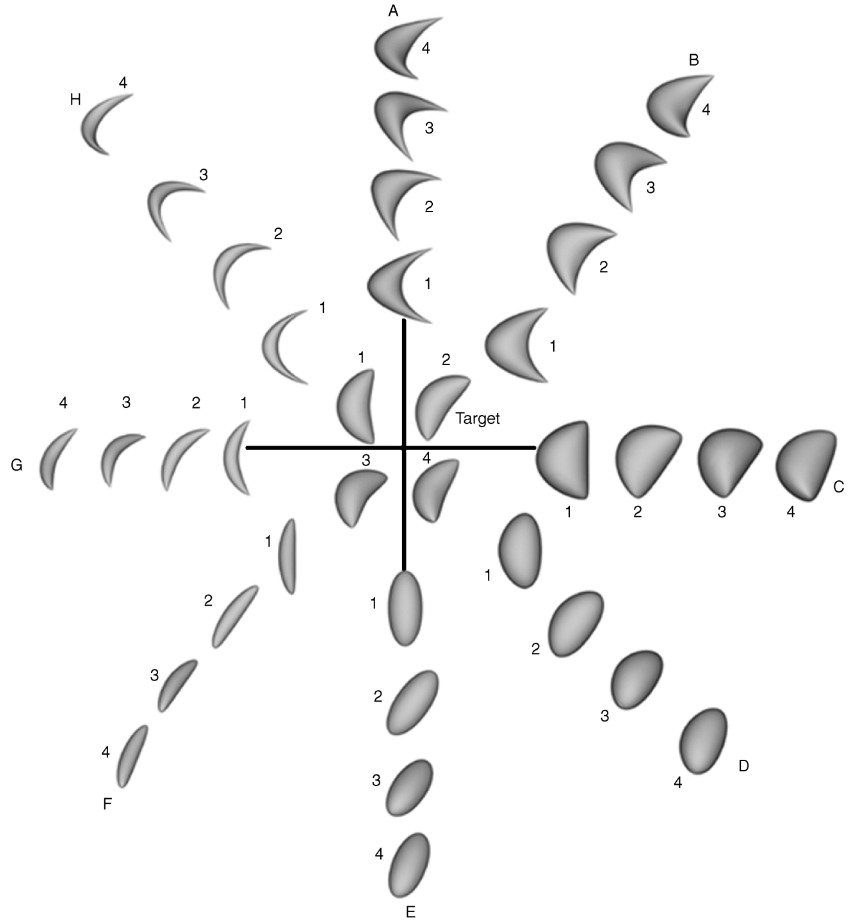

Figure 6. 3D stimuli used in Experiment 3. Shapes are presented (1) under an orientation of zero degree of rotation (i.e. same orientation as in Experiment 2), (2) with a rotation of 35 degrees around the X axis and 35 degrees around the Y axis, (3) with a rotation of 35 degrees around the X axis and 35 degrees around the Z axis, and (4) with a rotation of 35 degrees around the Y axis and 35 degrees around the Z axis.

Error rates were not analyzed since they were quite low (2.9% overall). The data show no speed-accuracy trade-off since the correlation between correct RTs and error rates was not significant ($r = -0.14$; *ns*).

Figure 7 displays the average correct RTs as a function of display size for each target type on positive and negative trials. Table 5 presents the results of the linear regression analyses of RTs as a function of display size in all conditions.

Linear regression analyses of RTs as a function of display size for each target type show that the display size effect is linear in all conditions. Ratios of positive over negative slopes approximate 0.5, which is congruent with a serial self-terminating strategy. These slopes are greater in the LNS and CONJ conditions than in the 1D-LS condition, which is congruent with the occurrence of conjunction and linear non-separability effects.

A three-way within-subjects ANOVA including the factors of target type (1D-LS, CONJ, LNS), target presence (present or absent) and display size (3, 5, 7 or 9 items) on the dependent variable of correct RTs was carried out. Main effects of target type [$F(2, 10) = 37.4$, $p < 0.001$], target presence [$F(1, 11) = 91.0$, $p < 0.001$], and display size [$F(3, 9) = 171.7$, $p < 0.001$] were obtained. These indicate a significant variation of RTs as a function of target type, shorter RTs when the target was present than when it was absent, and a linear increase of RTs as a function of the number of items, as shown by the regression analyses (Table 5).

All pairwise interactions as well as the target type × target presence × display size interaction [$F(6, 66) = 6.7$, $p < .01$] were significant (all p's $< .01$). A breakdown of the three-way interaction was conducted to verify the occurrence of the conjunction and linear non-separability effects separately for positive and negative trials. On positive trials, the display size effect was weaker in the 1D-LS condition than in either the CONJ [$F(3, 33) = 11.6$, $p < .001$] or the LNS [$F(3, 33) = 15.5$, $p < .001$] conditions, thereby confirming the conjunction and linear non-separability effects. These effects are confirmed for negative trials as well, with a weaker display size effect in the 1D-LS condition than in either the CONJ [$F(3, 33) = 36.1$, $p < .001$] or the LNS [$F(3, 33) = 21.4$, $p < .001$] conditions.

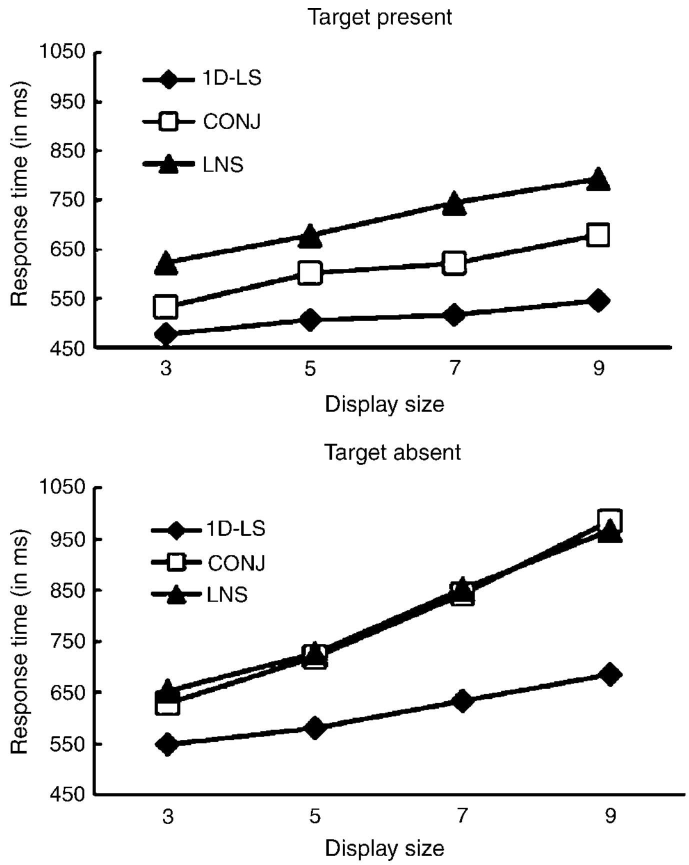

Figure 7. Average RTs in Experiment 3 as a function of display size for each target type on positive and negative trials.

An additional, between-experiment ANOVA was also carried out in order to assess whether there is any difference in the pattern of the CONJ and LNS effects upon search rates when stimuli were displayed in a fixed (Experiment 2) vs. random (Experiment 3) depth orientation. In this new analysis, the factor experiment was treated as a between-subject variable. This new analysis completely replicates the effects reported above for Experiments 2 and 3 when analyzed separately, which entirely overlap. In addition, the main effect of experiment [$F(1, 22) = 4.6$, $p < .05$] as well as the interactions of target presence × experiment [$F(1, 22) = 4.2$, $p < .05$], display size × experiment [$F(3, 66) = 11.4$, $p < .001$] and target presence × display size × experiment [$F(3, 66) = 5.9$, $p < .05$] were significant. These indicated a larger effect of target presence and of display size, as well as a larger impact of target presence on the display size effect in Experiment 3 than in Experiment 2. Thus, depth rotation had an impact on performance. Notably, the slopes of RTs as a function of display size were 1.8 and 2.0 times greater, on average, with random than fixed depth orientations on positive and negative trials, respectively. However, other interactions that include the factor experiment were not significant (all p's > .05). Most importantly, the interaction of experiment × target type × display size was not significant [$F(6, 132) < 1$]. This indicates that the magnitude of the conjunction and linear non-separability effects on search rates is not significantly different between Experiment 2 (i.e. stimuli with fixed depth orientation) and Experiment 3 (i.e. stimuli with random depth orientation). These results conclusively show that the conjunction and linear non-separability effects were unaffected by depth rotation.

Discussion

The purpose of Experiment 3 was to examine the impact of depth rotation on the conjunction and linear non-separability effects with 3D stimuli. The results are straightforward: the magnitude of these effects on visual search rates was unaffected by depth rotation. However, a cost of depth rotation was observed on other factors; cf. main effect of orientation and interactions of orientation with display size and target presence. For instance, the display size effect on RTs was about doubled with the random orientations relative to a fixed orientation. This indicates that the manipulation of stimulus orientation applied in Experiment 3 was sufficiently strong to reproduce the rotation cost on performance that was found in previous studies. Therefore, it is concluded that the shape representations indexed by the conjunction and linear non-separability effects are invariant to depth rotation.

Experiment 4

There are two aspects of the orientation manipulation used across Experiments 1, 2, and 3 that could be conceived as problematic with respect to the conclusion of the orientation-invariance of the shape representations

	Positive trials			Negative trials			
Condition	Intercept (ms)	Slope (ms/item)	R^2	Intercept (ms)	Slope (ms/item)	R^2	Pos/neg ratio
1D-LS	455.4	21.6	0.97	494.8	46.3	0.99	0.47
CONJ	491.3	46.0	0.96	494.1	119.3	0.99	0.39
LNS	563.6	57.8	0.99	531.3	106.7	0.99	0.54

Table 5. Linear regressions of correct RT for each condition in Experiment 3.

mediating the conjunction and linear non-separability effects. One is that the fixed vs. random orientation conditions are not matched with respect to task difficulty. From the results of the previous experiments, it is obvious that having items in random orientations makes the task more difficult than if all items have the same orientation. It was relevant to demonstrate this difference in order to show that indeed the visual search task and stimuli used do show a performance cost with rotated stimuli that is of a similar nature to that shown previously in the literature. Although we believe that this difficulty difference across orientation conditions is unlikely to invalidate our observations pertaining to the orientation invariance of visual shape representations, it would remain preferable to have a test where overall task difficulty is matched across orientation conditions. A more significant problem however, is that using stimuli in random orientations does not guarantee a systematic orientation mismatch between the target and distractors, which obviously was the intended outcome of this manipulation. New experiments were designed to resolve these potential problems. On every trial, the two distractor shapes were displayed in either matching or mismatching orientations and at least two items were shown at each of four possible orientations. In a "matching-orientations" trial using distractors A and G for instance, each of these shapes was shown in orientations 1, 2, 3, and 4. In contrast, in a "mismatching-orientations" trial, distractor A was replicated twice at each of two orientations (e.g. 1 and 2) and distractor G was also replicated twice at the two remaining orientations (e.g. 3 and 4). Within the constraint of these rules, the orientation assignment of distractor shapes was random. On target-present trials, the target shape was shown in addition to the eight distractors and its orientation was determined randomly. On target-absent trials, an additional instance of one of the distractor shapes was chosen randomly (with the constraint that each possible shape was presented an equal number of times across the experiment) and its orientation obeyed the constraints of the orientation condition to which this trial was assigned.

From this design, it can be noted that if the shape representations mediating the conjunction and linear non-separability effects are orientation-specific, then these effects should occur in the "matching orientations" condition but not with "mismatching orientations" since, in this case, no distractor pair entertains the proper shape relation to the target to cause these effects. In contrast, if the shape representations upon which the conjunction and linear non-separability effects are based are orientation-invariant, then the magnitude of these effects will be unaffected by the orientation condition. The advantages of this new experimental design over the previous one are that the overall level of difficulty is matched across orientation conditions since an equal number of items at each possible orientation is used in both cases. Moreover, with the orientation of items being determined by rule instead of randomly, the orientation relations between the distractors and between the target and distractors are precisely determined.

Another noteworthy feature of this new experimental design is that the total number of items displayed on any given trial is nine. With the number of items remaining fixed, this means that our assessment of the conjunction and linear non-separability effects will not be based on search rates, but rather on how they impact RTs with a display size of nine. Given the results of the previous experiments, it is clear that with such a display size, the conjunction and linear non-separability effects previously demonstrated on search rates directly translate into absolute RT differences that allow the intended assessment of these effects.

Experiment 4 effects using 2D shapes (Figure 1) whereas Experiments 5 and 6 assessed depth rotations using 3D shapes (Figures 4 and 6).

Method

Participants

Twelve students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the experiment and all had normal or corrected acuity.

Stimuli

The stimuli were the 2D shapes used in Experiment 1, and the materials were the same as in Experiments 2 and 3. The stimuli could be presented in one of four different orientations, each separated by a planar rotation of 90 degrees.

Procedure

The present experiment manipulated the factors of target type (1D-LS, CONJ and LNS), orientation (matching or mismatching), and target presence (present or absent). Each subject completed two blocks of 240 trials each. The order of the blocks was determined randomly. The different levels of each factor were intermingled within each block, and there were an equal number of trials for each condition across blocks. On negative trials, four distractors of each type were presented (e.g., for a CONJ trial using the distractors set A-G, four distractors A and four distractors G were presented). In order to maintain a constant number of items across positive and negative trials, there was one more instance of a distractor shape than of the other on negative trials. On these trials, the total number of exemplars of each distractor shape within each block was equal. Each distractor was presented in one of four possible orientations. In the matching-orientations condition, the two distractor types (i.e., distractors A and G in the above example) were

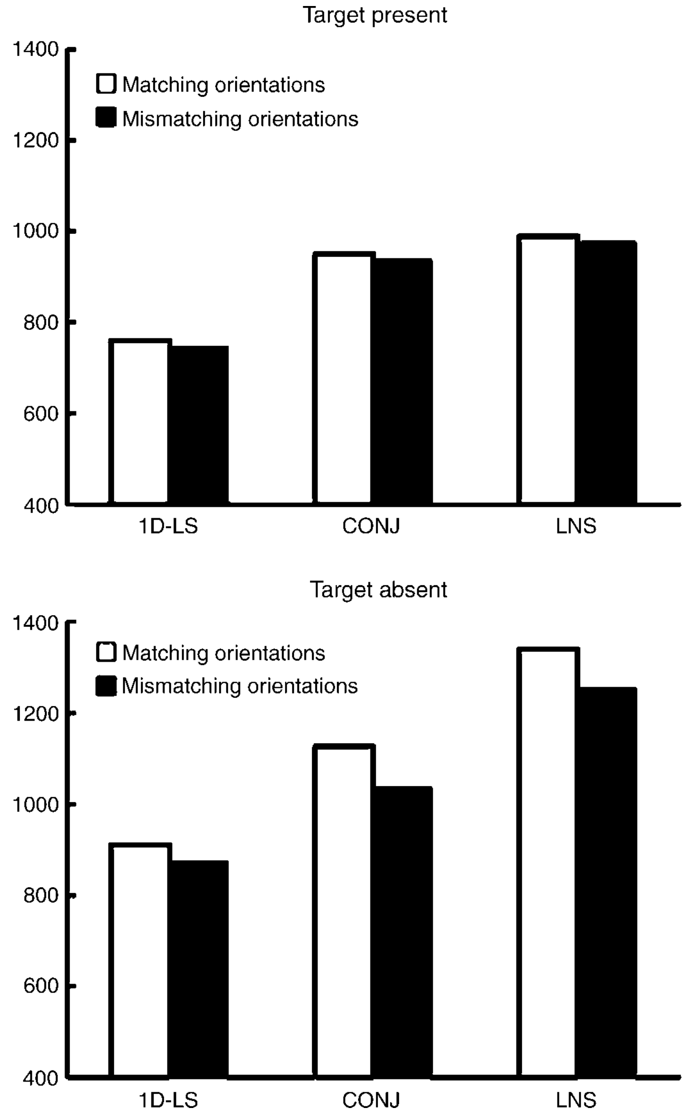

Figure 8. Average RTs in Experiment 4 as a function of target type for each orientation condition on positive and negative trials.

displayed in each of the four possible orientations. In the mismatching-orientations condition, two instances of a distractor were displayed in each of two orientations (determined randomly) and two instances of the other distractor were displayed in each of the other two orientations. The rest of the procedure was the same as in Experiments 1, 2, and 3.

Results

RTs that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 142 data points for the complete experiment (2.5% of trials). The error trials were also excluded from the RTs analyses. Error rates were not analyzed since they were quite low (2.7% overall). The data show no speed-accuracy trade-off since the correlation between correct RTs and error rates was 0.04 (*ns*).

Figure 8 displays the average correct RTs as a function of target type for each orientation condition on positive and negative trials.

A three-way within-subjects ANOVA including the factors of target type (1D-LS, CONJ, LNS), orientation (matching or mismatching), and target presence (present or absent) on the dependent variable of correct RTs was carried out. Main effects of target type [$F(2, 22) = 119.9$, $p < 0.001$], orientation [$F(1, 11) = 25.0$, $p < 0.001$], and target presence [$F(1, 11) = 160.5$, $p < 0.001$] were obtained. These indicate a significant variation of RTs as a function of target type, shorter RTs when distractors were in different orientations than when they were in the same orientation, and shorter RTs when the target was present than when it was absent.

Only the interactions of orientation × target presence [$F(1, 11) = 7.9$, $p < 0.025$] and of target type × target presence [$F(2, 22) = 19.9$, $p < 0.001$] were significant. Simple effects of the interaction of the orientation × target presence interaction showed that the orientation effect was significant on negative [$F(1, 11) = 23.2$, $p < 0.001$] but not on positive [$F(1, 11) = 2.4$, *ns*] trials. The significant effect of orientation on negative trials reflects the fact that RTs were larger with matching (1126 ms) than with mismatching orientations (1056 ms). Simple effects of the interaction of target type × target presence indicate significant target type effects on both positive [$F(2, 22) = 155.4$, $p < 0.01$] and negative [$F(2, 22) = 70.0$, $p < 0.01$] trials. The interaction is therefore attributed to different profiles for the target type effect on positive and negative trials. Despite these different profiles however, pairwise comparisons conducted separately for positive and negative trials confirm the presence of the conjunction and linear non-separability effects in both cases. Thus, on positive trials, RTs were shorter in the 1D-LS condition than in either the CONJ [$F(1, 11) = 149.3$, $p < .001$] or the LNS [$F(1, 11) = 413.5$, $p < .001$] conditions. On negative trials too, the RTs were shorter in the 1D-LS condition than in either the CONJ [$F(1, 11) = 41.3$, $p < .001$] or the LNS [$F(1, 11) = 110.7$, $p < .001$] conditions.

Of particular interest in the present context is the fact that neither the two-way interaction of target type × orientation [$F(2, 22) = 1.0$, *ns*] nor the three-way interaction of target type × orientation × target presence [$F(2, 22) = 1.5$, *ns*] were significant. These observations indicate that the factor of stimulus orientation had no impact on the magnitude of the conjunction and linear non-separability effects observed in the present experiment.

Discussion

The present experiment was designed to minimize the task-difficulty difference between orientation conditions which existed in the previous experiments as well as to have a more precise control over the orientation of stimuli than in the random-orientation condition of Experiments 1 and 3. In Experiment 4, all the possible stimulus orientations were present on every trial in order to avoid any possible confound to contaminate the orientation factor. In this better controlled experiment, the results demonstrate that the shape representations which mediate the conjunction and linear non-separability effects are invariant across planar rotations. Thus, the effects of conjunction and linear non-separability were completely maintained when the distractors and the target were shown in mismatching orientations relative to when they were presented in matching orientations.

Experiment 5

Experiment 5 was designed similarly to Experiment 4 except that the stimuli used were those with a 3D aspect shown in Figures 4 and 6 and that stimuli were rotated in depth rather than on the picture plane.

Method

Participants

Twelve students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the experiment and all had normal or corrected acuity.

Stimuli

The materials and stimuli were the same as in Experiments 2 and 3. The stimuli could be presented in one of the four depth orientations used in Experiment 3.

Procedure

The procedure was the same as in Experiment 4.

Results

RTs that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 125 data points for the complete experiment (2.1% of trials). The error trials were also excluded from the RTs analyses. Error rates were not analyzed since they were rather low (5.1% overall). The correlation between correct RTs and error rates was negative and significant ($r = -0.63$; $p < .05$). This suggests a speed-accuracy trade-off which, however, is only manifest with respect to the effect of target presence. Indeed, while RTs were substantially shorter on positive (1097 ms) than negative (1541 ms) trials, the target presence effect on error rates was very large and in the opposite direction (positive trials: 2.0%; negative trials: 8.5%). Confirming this, an ANOVA conducted on error rates with factors of target type (1D-LS, CONJ, LNS), orientation (matching or mismatching), and target presence (present or absent) only showed a significant effect of target presence [$F(1, 11) = 15.8$, $p < 0.005$]. All other main effects and interactions failed to reach significance (all p's > .05).

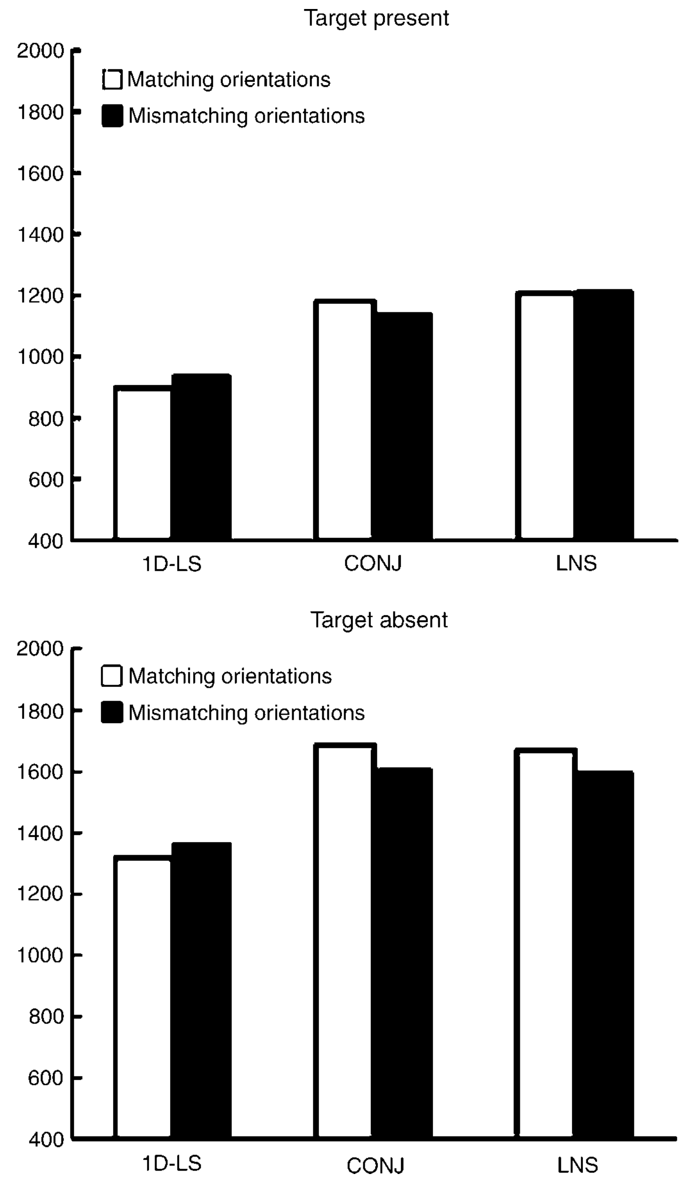

Figure 9. Average RTs in Experiment 5 as a function of target type for each orientation condition on positive and negative trials.

Figure 9 displays the average correct RTs as a function of target type for each orientation condition on positive and negative trials.

A three-way within-subjects ANOVA including the factors of target type (1D-LS, CONJ, LNS), orientation (matching or mismatching), and target presence (present or absent) on the dependent variable of correct RTs was carried out. Main effects of target type [$F(2, 22) = 69.2$, $p < 0.001$], and target presence [$F(1, 11) = 45.9$, $p < 0.001$] were obtained. These indicate a significant variation of RTs as a function of target type, and shorter RTs when the target was present than when it was absent. The main effect of orientation was not significant [$F(1, 11) < 1$].

All interactions failed to reach significance (F's < 1), except for that of orientation × target type which was significant [$F(2, 22) = 7.3$, $p < 0.005$]. This significant interaction was broken down into pairwise comparisons designed to assess the conjunction and linear non-separability effects separately for matching and mismatching orientations. With matching orientations, RTs were larger in the CONJ and LNS conditions than in the 1D-LS condition ([$F(1, 11) = 67.8$, $p < 0.001$]; [$F(1, 11) = 88.6$, $p < 0.001$], respectively). With mismatching orientations, RTs were also larger in the CONJ and LNS conditions than in the 1D-LS condition ([$F(1, 11) = 63.2$, $p < 0.001$]; [$F(1, 11) = 124.6$, $p < 0.001$], respectively). Thus, both the conjunction and linear non-separability effects are confirmed for both levels of the orientation factor and the orientation × target type interaction must therefore be attributed to a modulation in the magnitude of these effects as a function of orientation. The F values obtained in our pairwise comparisons would seem to suggest that both the conjunction and linear non-separability effects have a greater magnitude on mismatching than matching orientations. This however, is based on the much smaller MSe's obtained for mismatching (9367 and 6209 for the conjunction and linear non-separability effects, respectively) than matching (18614 and 14748 for the conjunction and linear non-separability effects, respectively) orientations. In fact, a direct examination of RTs (see Figure 9) reveals that the magnitude of both the conjunction and linear non-separability effects was substantially weaker with mismatching (222 ms and 254 ms, respectively) than matching orientations (324 ms and 330 ms, respectively).

Discussion

Experiment 5 examined the impact of depth rotation on the conjunction and linear non-separability effects using a design that offers improved experimental control over the previous experiments. The results showed a reduction in the magnitude of the conjunction and linear non-separability effects when items were shown in mismatching depth orientations relative to when they were displayed in matching orientations. It may be noted however that despite this reduction, the conjunction and linear non-separability effects remained highly significant with mismatching orientations.

One possible interpretation of the significant reduction of the conjunction and linear non-separability effects with mismatching orientations is that the shape representations mediating the conjunction and linear non-separability effects are unstable across viewpoints. Taken together with the results of Experiment 4, these observations would suggest that these shape representations are orientation-specific with respect to depth rotations but orientation-invariant with respect to planar rotations.

In defense of the hypothesis of depth orientation-invariance however, it may be noted that the depth cues offered by our 3D stimuli were relatively weak. This may have interfered with the perception of their 3D structure, and therefore with the construction of a representation that offers orientation-invariance for depth rotation. Indeed, the available evidence indicates that the perception of the 3D aspect of visual shapes as well as resistance to depth rotation are improved by depth cues such as shading, texture, and stereoscopy (e.g. Burke, 2005; Cutting & Millard, 1984; Johnston, Cumming, & Parker, 1993; Tarr, Kersten, & Bülthoff, 1998; Todd & Akerstrom, 1987). This suggestion thus raises doubts as to the appropriateness of the stimuli used in Experiment 5 to assess the effects of depth rotation. In order to resolve this uncertainty, Experiment 6 was conducted using stimuli that offer enhanced depth information.

Experiment 6

The design of Experiment 6 is identical to that of Experiment 5 but the stimuli were different in that the depth information they offered was enhanced by the rich texture that was applied on their surfaces (see Figure 10). If the conjecture proposed above regarding the role of depth information in offering shape representations improved resistance to depth rotation is correct, then the modulation of the conjunction and linear non-separability effects that was produced by depth rotation in Experiment 5 will be reduced or eliminated in Experiment 6.

Method

Participants

Twelve students from the Université de Montréal took part in the experiment. All were naive as to the purpose of the experiment and all had normal or corrected acuity.

Stimuli and procedure

The materials, stimuli, and procedure were the same as in Experiment 5 except that the stimuli used were those displayed in Figure 10. These represent the same objects as those used in Experiment 5 except for the addition of a gray-level texture that improves the appreciation of the depth orientation of the surfaces of the objects.

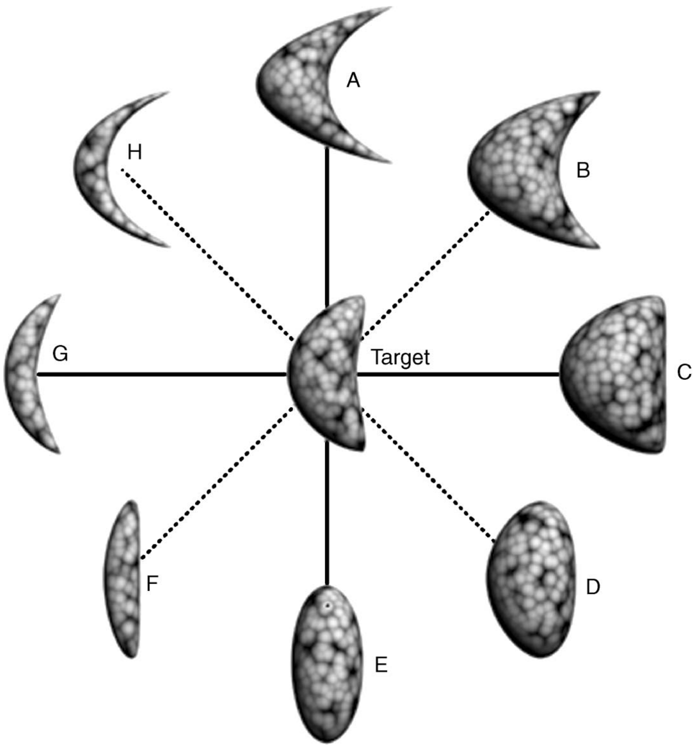

Figure 10. Illustration of the stimuli used in Experiment 6. They are presented according to the same conventions as used in Figure 5.

Results

RTs that were more than three standard deviations away from a participant's average for a given condition were eliminated, resulting in the exclusion of a total of 96 data points for the complete experiment (1.9% of trials). The error trials were also excluded from the RTs analyses. Error rates were not analyzed since they were relatively low (4.6% overall). The data show no speed-accuracy trade-off since the correlation between correct RTs and error rates was 0.07 (*ns*).

Figure 11 displays the average correct RTs as a function of target type for each orientation condition on positive and negative trials.

A three-way within-subjects ANOVA including the factors of target type (1D-LS, CONJ, LNS), orientation (matching or mismatching), and target presence (present or absent) on the dependent variable of correct RTs was carried out. Main effects of target type [$F(2, 22) = 56.4, p < 0.001$], target presence [$F(1, 11) = 21.8, p < 0.005$], and of orientation [$F(1, 11) = 11.8, p < 0.01$] were obtained. These indicate a significant variation of RTs as a function of target type, shorter RTs when the target was present than when it was absent, and slightly shorter RTs with mismatching (1360 ms) than matching (1383 ms) orientations.

Only the interaction of target type × presence was significant [$F(2, 22) = 22.0, p < 0.001$]; with $F < 1$ for all others. Simple effects analyses of the target type × presence interaction revealed greater RTs in the CONJ and LNS conditions than in the 1D-LS condition on both positive and negative trials (positive trials: CONJ vs. 1D-LS [$F(1, 11) = 103.4, p < 0.001$]; LNS vs. 1D-LS [$F(1, 11) = 183.6, p < 0.001$]; negative trials: CONJ vs. 1D-LS [$F(1, 11) = 66.8, p < 0.001$]; LNS vs. 1D-LS [$F(1, 11) = 45.7, p < 0.001$]).

With respect to the main issue assessed in Experiment 6, a detailed examination of RTs shows a complete invariance of both the conjunction and linear non-separability effects as a function of the orientation condition. Thus, the magnitude of the conjunction and linear non-separability effects with matching orientations was of 282 ms and 241 ms, respectively. With mismatching orientations, the corresponding values are of 276 ms and 273 ms, respectively.

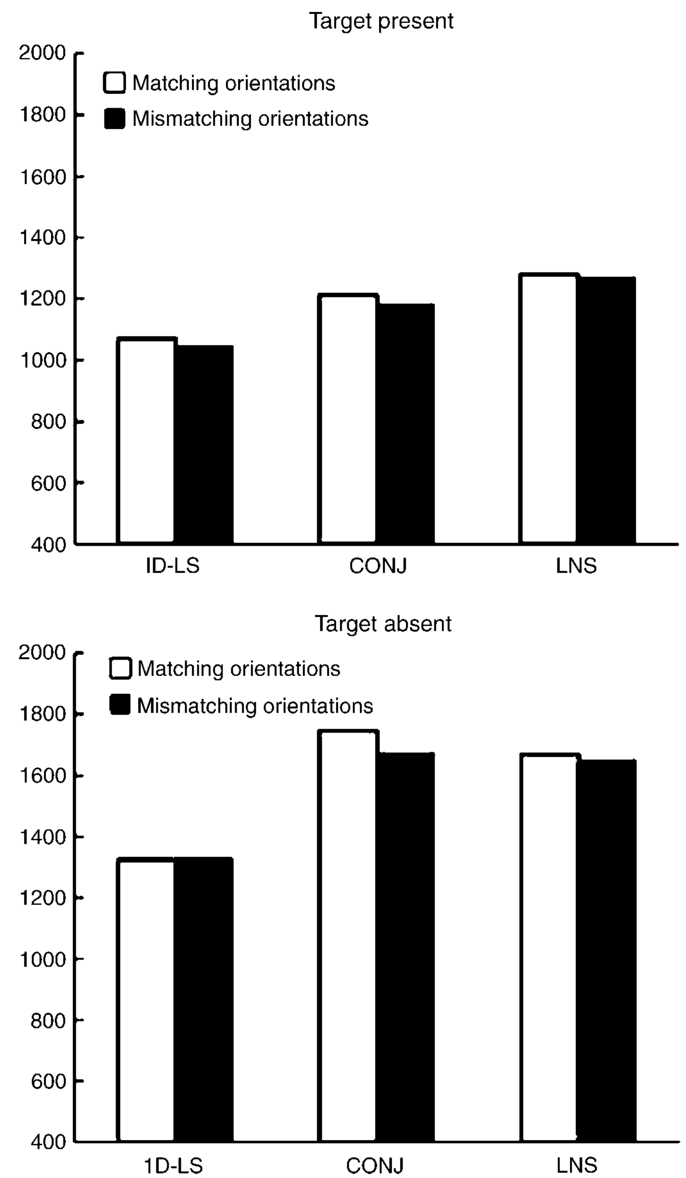

Figure 11. Average RTs in Experiment 6 as a function of target type for each orientation condition on positive and negative trials.

Discussion

Experiment 6 was a replication of Experiment 5 but using textured stimuli that offer improved depth information. This change led to a substantially different outcome since the results of Experiment 6 demonstrate conjunction and linear non-separability effects that are completely unaffected by whether the stimuli were displayed in matching or mismatching orientations. This finding indicates that the shape representations mediating these effects in Experiment 6 are invariant across rotations in depth. This therefore, supports the conjecture proposed in the discussion of Experiment 5 that the orientation-dependency suggested by the results of that experiment are attributable to the relatively poor depth information offered by the stimuli used.

General discussion

The experiments reported in this paper assessed the orientation-specificity of the shape representations that mediate the conjunction and linear non-separability effects with respect to both planar and depth rotations. We have argued in the Introduction that past studies investigating the issue of orientation-specificity through a direct approach of measuring rotation costs on performance are problematic since they allow no clear conclusion. Specifically, the modulation of response latency or accuracy as a function of the degree of rotation is theoretically ambiguous and, in addition, it may originate from the orientation-specificity of one particular processing stage involved in the task even though the others (even if participating in shape representation) are not. To avoid such ambiguities, we have proposed and applied a novel experimental approach that is based on second-order rotation effects. Specifically, the present investigation examined the impact of image plane rotations of 2D stimuli and that of depth rotations of 3D objects on the magnitude of the conjunction and linear non-separability effects in the visual search task.

Summary of findings and interpretation

In Experiments 1, 2, and 3, we compared a condition where stimuli all had the same orientation to another in which each item had its own orientation determined randomly and independently. Large main effects of this manipulation of orientation were found on performance and this factor also interacted with the display size and target presence effects for both planar and depth rotations. Specifically, the display size and target presence effects were magnified substantially with random orientations compared to a fixed orientation. These observations indicate that performance was indeed sensitive to planar and depth rotations, which is congruent with several past investigations involving such manipulations (see Introduction). However, and most importantly in the present context, the factor of stimulus orientation did not interact with target type; i.e. the magnitude of the conjunction and linear non-separability effects was unaffected by stimulus orientation. This led to the conclusion that the shape representations subtending the target type effects examined are orientation-invariant; i.e. that they are stable across planar and depth rotations.

In Experiments 4, 5, and 6, the issue was re-examined using a different method whereby we contrasted conditions in which instances of each shape serving as distractors were displayed in matching vs. mismatching orientations. Assuming an orientation-specific representation of the stimuli, the shape relations between the target and distractors that define the target type conditions used (1D-LS, CONJ, and LNS) are verified with matching orientations but they are violated with mismatching orientations. The results with planar stimulus rotations fully replicated the resistance of the target type effects to stimulus rotation found in Experiment 1. This supports the conclusion that the shape representations mediating the conjunction and linear non-separability effects are orientation-invariant with respect to planar rotations.

The findings pertaining to depth rotations were more complex. Experiment 5 showed that the magnitude of the conjunction and linear non-separability effects was reduced with mismatching orientations relative to matching orientations. This finding is attributable not to the orientation-specificity of the representations involved however, but rather to the poor depth information offered by the stimuli used in Experiment 5. Thus, Experiment 6 fully replicated the method and design of Experiment 5 except that the stimuli offered enhanced depth information by using objects with a rich surface texture. The results showed target type effects that were invariant across orientation conditions, thereby indicating that depth rotation invariant shape representations subtend the target type effects studied.

This contrast between the observations obtained from Experiments 5 and 6 highlights important points regarding the experimental design used as well as the importance of proper depth information for shape perception. With respect to the experimental design, it may be noted that our main conclusions rest on the absence of an orientation $\times$ target type interaction. This could be conceived as problematic in the context of observations that would suggest an insensitivity in our measurements or in the design itself to this interaction; i.e. that for some reason it would be difficult to have this interaction reach significance. The large impact that the presence/absence of texture on the object surfaces has had on the occurrence of the crucial orientation $\times$ target type interaction indicates that measurement or design sensitivity was not an issue.

The contrasting results of Experiments 5 and 6 also point to a marked susceptibility of shape representations to the richness of depth cues. Specifically, our findings indicate, with respect to depth rotations, orientation-specific representations with relatively poor depth information, and orientation-invariant representations with improved depth information. Such observations are congruent with past findings demonstrating a contribution of depth information to the perception of the 3D structure of visual shapes and resistance to depth rotation (e.g. Burke, 2005; Cutting & Millard, 1984; Johnston et al., 1993; Tarr, Kersten, et al., 1998; Todd & Akerstrom, 1987).

Although this is pure conjecture, it appears that the shape dimension that is most likely to suffer from poor depth cues is curvature. Indeed, even with scrutiny, it is rather difficult to obtain a clear notion of the actual curvature of our textureless 3D objects (see Figure 7 for instance). This is much easier with textured objects. In contrast, the perception of elongation for the stimulus class used here subjectively appears highly resistant to depth rotation even with the textureless stimuli (Figure 7).

Overall then, the two experimental methods used here to manipulate stimulus orientation provide results indicating that the shape representations subtending the conjunction and linear non-separability effects in our visual search tasks are fully orientation-invariant; i.e. for both planar and depth rotations. This is all the more remarkable that these demonstrations were obtained using both indexes of conjunction and linear non-separability effects, which clearly appear to implicate distinct mechanisms (see Saumier & Arguin, 2003). This highlights the robustness of our observations with respect to the issue of the orientation-invariance of shape representations in humans. In addition, this suggests that the shape representations involved in both target type effects may either be the same or, if they are different, that they have orientation-invariance as a common property.

Orientation-invariance with respect to planar rotations may not appear that greatly surprising if one considers the requirements of such a representation. Indeed, invariance to planar rotations only needs to involve 2D information. What is necessary to achieve this type of invariance is limited to achieving a code for shape representation that disregards, or abstracts away, information pertaining to retinal orientation. Orientation-invariance with respect to depth rotations is more striking however, since it suggests that shape representations must, on the one hand, integrate the depth information (or a subset thereof) that defines the shape of an object in 3D, and on the other hand, disregard information pertaining to the particular viewpoint from which the object was seen.

Methodological considerations

A crucial assumption in the second-order approach used here to investigate the effect of stimulus rotation is that it is possible to assess the orientation-specificity of a particular stage of shape representation independently of the others that might be involved in performing the task requested. The present observations demonstrate that this is indeed possible, thereby validating the second-order approach for the study of rotation effects. Thus, the rotation costs found in Experiments 1, 2, and 3 on overall RTs and on the magnitude of the display size and target presence effects indicate that there is at least one processing stage that is involved in carrying out the task which is orientation-specific. Independently, the same data set demonstrates that the processing stages tapped by the conjunction and linear non-separability effects are orientation-invariant.

The present findings also demonstrate that it is possible to resolve ambiguities inherent to data sets based on a direct approach of measuring performance costs of rotation (cf. Liu et al., 1999; Tjan & Legge, 1998). Specifically, the lack of rotation costs on performance may be due to orientation-invariant representations or alternatively, to a method that lacks sensitivity to rotation effects. Conversely, significant rotation costs may indicate orientation-specific representations or alternatively, they may be a function of the alteration of stimulus information by rotation. In the present study, the stimulus rotations used were obviously sufficient to produce the performance costs noted in Experiments 1, 2, and 3 (see above). This means that the orientation-invariance of the conjunction and linear non-separability effects is not a function of a poorly constructed experiment that would be incapable of showing rotation effects, but instead that it is a true reflection of the capacity for orientation-invariance in human shape perception. This capacity of the second-order approach to disambiguate between observations due to experimental design problems, changes in stimulus information, and properties of the shape representations of interest indicates that it should be privileged over a direct approach for the study of rotation effects.

As far as we can establish, there is only one other published study that has provided evidence for orientation-invariant shape representations while demonstrating in the same data set that the orientation manipulation was powerful enough to affect visual processing. This study may be conceived as an instance of the second-order approach advocated here. Dux and Harris (2007) examined the attentional blink affecting a second target (T2) within a rapid serial presentation of objects as a function of the orientation of the first target (T1) or of distractors. Their results indicate that T2 detection was more impaired if T1 was rotated by 90 deg than if it was upright or upside-down. In contrast, the orientation of distractors had no impact on the magnitude of the attentional blink. Thus, rotation effects interacted with the status (target or distractor) of the rotated stimuli. From their findings, the authors concluded "that the visual representations involved in the preliminary recognition of familiar objects are viewpoint-invariant and that viewpoint costs are incurred when these objects are consolidated for report"

(p. 47). Interestingly, this conclusion implies an order of orientation-specific and invariant processes that is reversed relative to the conjecture proposed by Bar (2001); see Introduction). Our present findings cannot adjudicate between these seemingly opposed theories. Rather, they may be considered compatible with either of them, provided that each assumes the existence of an orientation-invariant processing stage to which our observations on the conjunction and linear non-separability effects may be mapped.

Generality of findings

The current evidence indicates that the shape representations subtending the conjunction and linear non-separability effects in the visual search task are orientation-invariant. One legitimate question is whether these representations are specific to the particular context of our experiments or instead that they reflect properties of the visual system that apply to other situations.

With respect to the stimulus class used, our stimuli are not particularly remarkable. They rather resemble various categories of simple real world shapes, especially fruits and vegetables, which gives them a degree of ecological validity. However, whether our findings are applicable to complex objects made of two or more subjectively distinct parts is unclear. As noted below (see next section), it is possible that the representation of the spatial relations of the parts of complex objects imposes specific constraints that cannot be addressed by the present data.

Regarding the task used in the present experiments, it may be noted that the visual search task is something that humans do frequently in daily life. It appears obvious that the present findings should minimally apply to this type of context. More significantly, the visual search task has been used abundantly in the past to investigate visual function. Apart from the fact that the method presents, as any other, some particular limitations, we are unaware of demonstrations that evidence from visual search might be irrelevant to other visual tasks. Actually, it rather appears that visual search evidence reflects the properties of the visual system that may be replicated using other methods. A strong example of this is the visual search evidence for the early independent processing of elementary visual properties such as form, color, or orientation (e.g. Neisser, 1967; Treisman & Gelade, 1980), which is now largely agreed upon given the converging evidence from other methods.

Another potential limitation to the generality of our findings is the fact that the current evidence for orientation-invariance rests on the conjunction and linear non-separability effects. It could be argued for instance that the shape representations addressed by these effects are rather specific and that they are rarely used in other contexts, be it daily life or other types of experimental tasks. We argue that this is not the case. As noted in the Introduction, the conjunction effect is assumed to reflect the processing stage whereby the features characterizing a shape along various dimensions are integrated. As such, this stage would be implicated on all occasions that an individual requires an integrated shape representation, which we assume should be quite frequent. The linear non-separability effect on the other hand, reflects the contrasting mechanisms that must be applied to discriminate the target from distractors depending on whether the target is linearly separable. It appears difficult to evaluate how much these mechanisms may be used in real-life contexts but it is clear that they are not exclusive to shape visual search experiments. Indeed, other researchers have found the same type of linear non-separability effect as shown here, but in the color (Bauer et al., 1996a, 1996b, 1998, 1999; D'Zmura, 1991) and orientation domains (Wolfe et al., 1992). In this respect, the linear non-separability effect can be conceived as reflecting mechanisms with a wide range application.

Finally, another issue is whether the present evidence may be compatible with the physiological data pertaining to the orientation-specificity/invariance of brain systems involved in shape perception. In this respect, the current evidence is mixed. Single-cell recordings in the inferotemporal cortex of the macaque indicate orientation-specific receptive fields in some studies (Logothetis, Pauls, & Poggio, 1995; Perrett et al., 1985) but orientation-invariant responses in others (Booth & Rolls, 1998; Hasselmo, Rolls, Baylis, & Nalwa, 1989). Similarly, functional brain imaging of the human visual cortex shows evidence for orientation-specific activation, even in high-level visual areas, in some studies (Grill-Spector et al., 1999) whereas others report orientation-invariant responses in some areas (James, Humphrey, Gati, Menon, & Goodale, 2002; Vuilleumier, Henson, Driver, & Dolan, 2002). As for behavioral observations then, physiological studies offer varied outcomes which most likely are a function of the stimulus class used and the stimulus properties that are manipulated, of the particular task required of participants, and in addition, of the particular brain areas examined. The present evidence for particular orientation-invariant shape representations stages along with indications that others stages may be orientation-specific, thus appears entirely congruent with the currently available data from physiology.

Implications for theories of shape perception

Overall, the evidence reported in the present experiments is compatible with shape perception theories that jointly assume the capacity for orientation-invariance of some representation stages, as well as other stages that are orientation-specific. This evidence would obviously exclude image-based theories which fail to derive explicit shape representations that can resist stimulus rotation, either on the image-plane or in depth. Conversely, theories that assume orientation-invariant representations throughout the processing stages involved in shape perception also appear incompatible with the present observations.

A particular case among theories of shape perception is the JIM model of Hummel and Biederman (1992; see also Hummel & Stankiewicz, 1996), which predicts depth orientation invariance but costs of planar rotation. We note that the latter prediction is based on the way the model codes the spatial relations among the components of complex objects. Indeed, these relations are coded in propositional terms such as above, below, or beside, which obviously makes them orientation-specific with respect to gravitational coordinates. The stimuli used in our experiments, however, are simple objects made of a single component. Since they involve no need to represent spatial relations among parts, they are not appropriate to assess this property of the Hummel and Biederman model.

Past discussions of shape representation and of orientation-invariance have frequently tended to imply that humans can only possess one particular form of explicit high-level shape representation. This is by no means necessary however, and the results of an experiment by Foster and Gilson (2002) actually suggest parallel processing streams for shape perception (see also Hayward, 2003 for a detailed discussion of this study). One would be orientation-invariant and it would operate similarly to what is suggested by structural description theories. The other would be orientation-specific and it would show properties such as those suggested by the image-based view.

The possibility of parallel shape processing streams—or, alternatively, of a sequence of processing stages within which for instance, orientation-invariance may build up progressively in part through the integration of depth information—may be compatible with the findings reported here. In fact, the ease with which participants seem to have lost depth rotation invariance given the relatively poor depth information in the stimuli of Experiment 5 might be conceived as support for a dual mode of shape representation in humans. For example, one might assume that an image-based system is stimulated by both 2D patterns and 3D shapes and that the structural description system is stimulated only to the extent that the depth information available is sufficient to actually support such a representation. Under these assumptions, the lack of depth rotation invariance in Experiment 5 could be explained by the fact that the depth information present was insufficient and that, on most trials, only an orientation-specific image-based representation was available to participants.

Conclusion

In summary, the results reported here show that the conjunction and linear non-separability effects are fully maintained following planar and depth rotations. This indicates that the visual shape representations subtending these effects are orientation-invariant for both planar and depth rotations. Conversely, Experiments 1, 2, and 3 have shown that RTs as well as the display size and target presence effects are magnified by the planar and depth rotations of stimuli. Overall, these observations suggest that some processing stages involved in shape perception are orientation-invariant and others are orientation-specific and that these stages can be teased apart with the approach of assessing second-order rotation effects used here.

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