Perception, 2007, volume 36, pages 1229 – 1243

doi:10.1068/p5686

Effect of spatial position on visual search for 3-D objects

Hiroyuki Umemura, Hiroshi Watanabe, Katsunori Matsuoka
Institute for Human Science and Biomedical Engineering, National Institute of Advanced Industrial Science and Technology, 1-8-31 Midorigaoka, Ikeda, Osaka 563-8577, Japan;
e-mail: h.umemura@aist.go.jp
Received 19 September 2006, in revised form 6 March 2007

Abstract. We examined whether the position of objects in external space affects the visual-search task associated with the tilt of 3-D objects. An array of cube-like objects was stereoscopically displayed at a distance of 4.5 m on a large screen 1.5 m above or below eye height. Subjects were required to detect a downward-tilted target among upward-tilted distractors or an upward-tilted target among downward-tilted distractors. When the stimuli consisted of shaded parallelepipeds whose upper/bottom faces were lighter than their side faces, the upward-tilted target was detected faster. This result was in accordance with the 'top-view assumption' reported in previous research. Displaying stimuli in the upper position degraded overall performance. However, when the shaded objects whose upper/bottom faces were darker than their side faces were displayed, the detection of a downward-tilted target became as efficient as that of an upward-tilted target only at the upper position. These results indicate that it is possible for the spatial position of the stimulus to promote the detection of a downward-tilted target when shading and perspective information are consistent with the viewing direction.

1 Introduction

One of the primary purposes of the visual system is to represent the external world in a format that is suitable for object recognition and control of behaviour (Marr 1982; McCarley and He 2000). Several researchers have suggested that the visual system rapidly accomplishes this demanding task by constraining the possibilities of encountered scenes according to basic facts pertaining to the world (Attneave 1954; Barlow 1961; Ramachandran 1989; Kleffner and Ramachandran 1992; von Grünau and Dubé 1994; McCarley and He 2000). This strategy is believed to be effective because the stimuli in the world we live in are not arbitrary or capricious but redundant and predictable. Certain properties of this world can be assumed and do not have to be repeatedly rediscovered (utilitarian theory of perception—Ramachandran 1989).

Several assumptions pertaining to the retinal images formed from 3-D scenes are thought to be used even in the early stages of visual processing: viewing direction (Enns and Rensink 1990; Reichel and Todd 1990; Sun and Perona 1996), illumination direction (Ramachandran 1989; Kleffner and Ramachandran 1992), and the concavity or convexity of object surfaces (Hill and Bruce 1993; Langer and Bülthoff 2001). The shape inferred from shading is likely to be ambiguous—a convex bump lit from the top and a concave dent lit from the bottom render the same 2-D image—and the visual system can resolve this ambiguity by using the heuristic that scenes are illuminated from above (top-lit assumption) because such a situation is generally more likely to be encountered in our environment (Ramachandran 1988; Kleffner and Ramachandran 1992).

The convexity of 3-D objects is yet another assumption used by the visual system (Johnston et al 1992; Hill and Bruce 1993), and one effect of this assumption is the well-known hollow-mask illusion in which a hollow mask is perceived as convex surface (Gregory 1970). This illusion is robust to the changes in lighting direction, suggesting that the expectation for faces to be convex outweighs the expectation for light to come in from above. Although this illusion is stronger for faces than it is for other objects, it is not solely confined to face-like objects (Hill and Bruce 1994; Langer and Bülthoff 2001). Thus, the visual system generally appears to expect objects to be convex.

The visual system apparently assumes the viewer's position to be relative to that of the objects—a 'top-view assumption' (Reichel and Todd 1990; von Grünau and Dubé 1994; McCarley and He 2000). The ground on which an observer stands is necessarily below the eye height, and the farther away the objects attached to the same ground are, the higher, in general, they will be placed in the field of view. Secondary supporting surfaces surrounding an observer are also usually placed below eye height; therefore, the objects that are placed on them can be more easily perceived and grasped. As this arrangement of stimuli contains no inherent physical regularities that make it less redundant than a similar but inverted arrangement of items attached to an overhanging surface, an efficient general-purpose system of representation would be expected to encode the display of items viewed from top. McCarley and He (2000) used globally receding top-visible surfaces (as if objects were attached to an underlying ground-like surface) and globally receding bottom-visible surfaces (as if objects were attached to an overhanging ceiling-like surface); the experiment required subjects to perform visual search on these surfaces. The researchers found that the subjects performed better when searching for ground-like displays, suggesting that the spatially and stereoscopically distributed items are more easily organised to represent an ecologically representative pattern.

The existence of such heuristics has been demonstrated in several studies, thereby providing evidence for search asymmetry (Enns and Rensink 1990, 1991; Kleffner and Ramachandran 1992; von Grünau and Dubé 1994; Sun and Perona 1996; Previc and Naegele 2001). Search asymmetry occurs whenever the ease with which the target can be found dramatically changes when the target and distractor stimuli are exchanged (Treisman and Souther 1985; Treisman and Gormican 1988). A target is easily detected only when it is unusually situated against the background of a more frequently experienced situation. Rapidly detected items are thought to contain features that correspond to the primitive elements in the human visual system (Enns and Rensink 1990). Von Grünau and Dubé (1994) performed an experiment with cube-like objects and observed search asymmetry. They found that upward-tilted targets (ie viewed from below) among downward-tilted distractors (ie viewed from above) were detected faster than downward-tilted targets among upward-tilted distractors. These results indicate that the search speed for 3-D objects depends on their tilt; it can be explained in terms of an observer's viewing direction—the visual system assumes that small objects are usually viewed from above.

The experiments presented in this paper were motivated by an issue related to the top-view assumption. People act in a 3-D environment and their viewing direction is changed according to their eye or head movements. When an observer looks up, objects that are hung from the ceiling or are floating in air become easier to see. As a result, the possibility of viewing objects from the bottom would increase and the top-view assumption would decrease the efficiency of visual processing. The main purpose of the present study was to examine whether the human visual system takes the observer's viewing direction into account and whether it can effectively use this information. Several studies have indicated that the visual system uses extraretinal information such as head movements on a horizontal plane for reconstructing 3-D scenes (Wexler et al 2001).

There are two ways in which the visual system can use information regarding the observer's viewing direction. First, the information that the viewing direction is upward could replace the top-view assumption with the bottom-view assumption. In this case, the reversal of search asymmetry would be observed; a downward-tilted target among upward-tilted distractors would be detected more easily than would an upward-tilted target among downward-tilted distractors. The second is that the information could bias the detection in a more moderate fashion that is implemented in a top–down manner. This possibility was investigated in visual-search experiments by Sun and Perona (1996) in which an array of 3-D objects that had perspective information was displayed on a background suggesting the context of a room. The researchers found that perspective information with the floor context improved the performance of the visual search, while the absence of a floor context or an inconsistent context impaired the search performance. This implies that visual-search tasks with 3-D objects are facilitated by the contexts that are given by visual information.

There would be a case in which the visual system was unable to use the information about the viewing direction. For example, Kleffner and Ramachandran (1992) found that the top-lit assumption primarily depended on retinal rather than on gravitational coordinates. That is, the assumption about a light source position was not affected by the direction in which the observer's head was oriented (face horizontal or face vertical). This implies that the visual system does not change its assumption regarding the light direction even though the assumption becomes invalid with the rotation of one's head. This inflexibility would be useful for avoiding the additional computational burden of correcting for head tilt in shape-from-shading processes (Kleffner and Ramachandran 1992).

Although little attention has been paid to the effect on the visual processing of an object's position in relation to that of the viewer in a large 3-D space, the effect of a position relative to eye direction was investigated in von Grünau and Dubé (1994). They found a visual-field anisotropy in which the visual-search asymmetry for the object direction was comparatively less pronounced in the upper visual hemifield (UVF). This visual-field anisotropy appears to reflect a higher probability that the tops of objects are in the lower visual hemifield (LVF) rather than in UVF.

In the present study, we distinguished between this anisotropy and the effect of the viewing direction by using a large-screen display to produce a nearly identical retinal image regardless of the display position and having the observers move their heads up or down to see the stimulus actually displayed above or below them.

2 General method

We used search fields consisting of 3-D objects, which were similar to those used by von Grünau and Dubé (1994)—upward-tilted targets amid downward-tilted distractors and vice versa—and examined the effect of the external position of the stimuli on the visual-search asymmetry. The effect of the display position in a simple visual-search task was investigated in a preliminary experiment.

2.1 *Apparatus*

Stimuli (1074 pixels wide × 512 pixels high) were generated and controlled by workstations (SGI Onyx 2) and projected onto a translucent screen (3 m^2) by a projector behind the screen; the subjects viewed this screen through liquid-crystal shutter glasses (Stereographics, CrystalEyes) with a 48 Hz refresh rate for each eye.

2.2 *Stimuli*

Each stimulus was a 2-D image of an array of 3-D cube-like objects (figure 1). Each item extended approximately 1 deg in width and 1.5 deg in height. Each stimulus contained 6, 15, or 21 items arranged in three rows. In the visual-search field, the centres of neighbouring items were horizontally and vertically separated by approximately 2 deg and 3 deg, respectively, with an additional random jitter of up to 0.5 deg. As a result, the visual-search fields were all approximately 9 deg high and had widths approximately ranging from 6 to 21 deg, depending on the number of distractors.

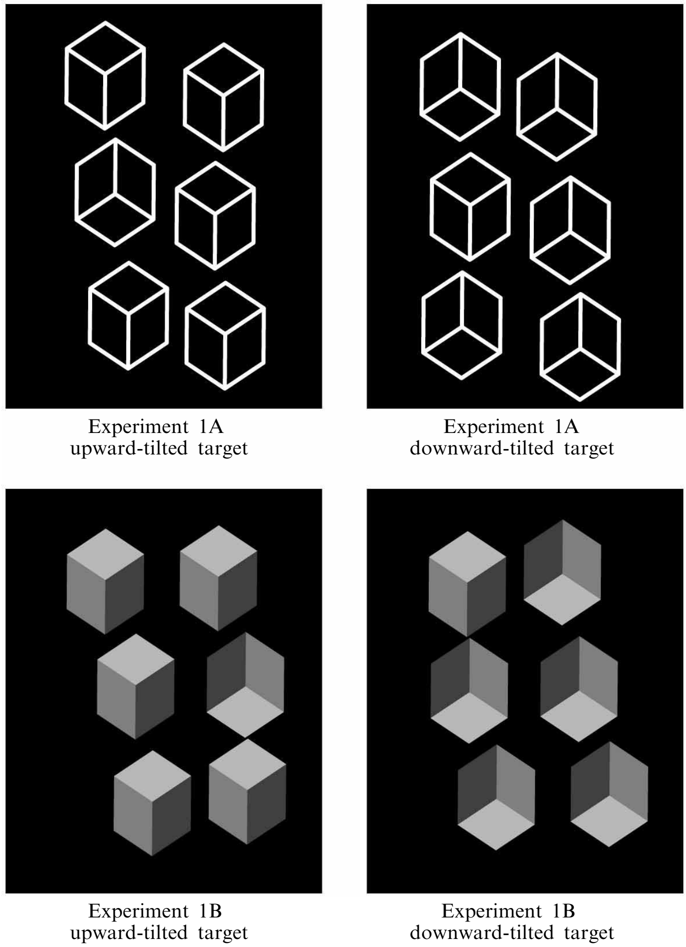

Figure 1. Examples of the stimuli used in experiment 1.

We controlled the tilts of the objects and their display positions with respect to the observer. In a downward-tilted target condition, the target was a downward-tilted object and the distractors were upward-tilted objects. In an upward-tilted target condition, the target was an upward-tilted object and the distractors were tilted downward.

The stimulus was displayed on the screen at a distance of 1.5 m from the subject; it was stereoscopically displayed with an apparent distance of 4.5 m (figure 2). Note that although the stimulus plane was displayed with depth, items on the plane were at the same depth. In an upper-position condition the centre of the stimulus was 1.5 m above eye height on the stereographic plane, and in a lower-position condition it was 1.5 m below eye height. On the actual screen, the stimuli were 0.6 m above or below eye height. As a result, the angle between a subject's eye level and the centre of a stimulus was 18° upward or downward.

2.3 *Procedure*

The experiment was conducted in a dark room. Subjects wore stereo glasses and stood at a distance of 1.5 m from the screen. During each session, the subject's head direction was tracked by an electromagnetic tracking sensor attached to the stereo glasses. Each trial began with the display of a fixation point on the centre of the screen at the eye height of the observer. When fixation was confirmed by the sensor, a second fixation point was displayed 1.5 m above or below eye height on a stereographic plane

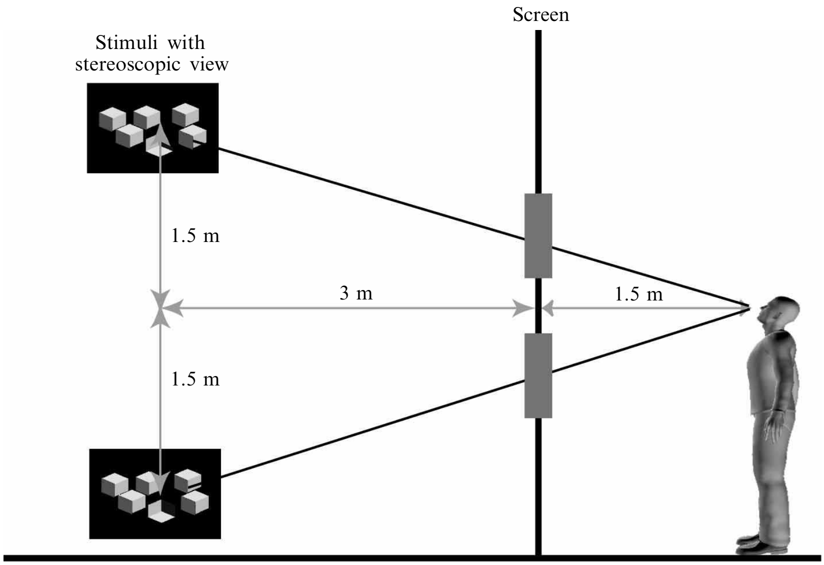

Figure 2. Experimental setting: Subjects wore stereo glasses and used a joystick with buttons to make responses.

that was 4.5 m from the subject; the subject moved his head in order to direct his gaze to the second fixation point. When the head direction changed by more than 17° in the direction from the first fixation to the second, the second fixation point disappeared and a stimulus was displayed after 0.5 s. Subjects were required to indicate the presence or absence of a target item by pushing the button of a joystick as soon as they had confirmed the fact. The stimulus remained on the screen until the subject responded; it remained for 2 s if the subject did not respond. Subjects were instructed to fixate on the first and second fixation points by moving their heads rather than their eyes, and were instructed to maintain their head direction until they made a response.

Each session included four combinations comprising two object-tilt and two display-position conditions, and there were 25 repetitions for each of the four combinations. A target was presented in approximately half the trials in each session. The order of presentation in each session was randomised for each subject. Sufficient practice sessions were held before the experimental sessions.

3 Preliminary experiment

The stimulus in the preliminary experiment was an array of 2-D line-drawn objects. The distractors were Ls that were all either upright or rotated by 90°, 180°, or 270°, and, from among the distractors, the target was an L rotated at an angle of 90°. The extent and separation of these items and the procedures were those described in section 2. Four subjects participated in the preliminary experiment. The response time (RT) for correct responses in the target-present condition across the number of items was 777 ± 159.6 ms (mean $\pm$ SD) when the stimulus was displayed at the upper position and 780 ± 112.9 ms when the stimulus was displayed at the lower position. The corresponding times for the target-absent condition were 782 ± 126.4 ms for the upper position and 767 ± 125.9 ms for the lower position. A two-factor (position, field size) within-subjects ANOVA on the correct RT data in the preliminary experiment showed no significant effect of the display position and no interaction in both the target-present condition and the target-absent condition. These results imply that the display position does not have an inherent effect on the visual-search procedures.

4 Experiment 1

The search items presented in experiment 1A were drawn with white lines on a black background, while those presented in experiment 1B were drawn by using a shading effect in which the upper/bottom face was the lightest (7 cd m^{-2}) and the other two faces were one-half and one-fourth as light (figure 1). The subjects consisted of ten men (22–34 years old) with normal or corrected-to-normal vision. Only one subject was aware of the experimental hypothesis. The subjects performed the task once under each of the six experimental conditions (experiments 1A and 1B, each with three different display sizes). The order of a set of six experimental sessions was randomised and counterbalanced among subjects.

4.1 *Results of experiment 1*

Data for experiments 1A and 1B were separately analysed. Trials with RTs exceeding 2000 ms (ie greater than the target display time) have been excluded from the data. We calculated the slope of the maximum-likelihood linear fit of the RTs as a function of display size for both the target-present and the target-absent trials. The mean RTs as a function of the display size for target-present trials, the mean error rate, and slopes for target-present trials in experiments 1 are listed in table 1. As the main indicator of search performance, we used the mean RTs for the target-present trials, which were analysed with a three-way within-subjects ANOVA (display position, object tilt, and display size). The mean RTs in experiments 1A and 1B are indicated in figure 3. The interesting variables in the present experiments are the display position and the object tilts. When the interaction between the display size and both or either of the other two factors was significant, we also performed a two-way within-subjects ANOVA (display position and object tilt) for the slopes in the target-present trials.

Table 1. Reaction times as a function of the number of items for target-present trials, mean error rate, and slopes for target-present and absent trials in experiments 1A and 1B.

Experiment	Position	Target tilt	Reaction time/ms			Error rate	Slope/ms per item	
			6 items	15 items	21 items		present	absent
1A	upper	upward	873	1076	1212	0.07	23	36
		downward	902	1152	1279	0.12	25	40
	lower	upward	827	1020	1167	0.06	23	36
		downward	895	1050	1200	0.09	20	40
1B	upper	upward	917	957	1063	0.04	9	33
		downward	889	1106	1231	0.09	23	38
	lower	upward	858	918	969	0.03	7	33
		downward	915	1032	1147	0.07	15	42

The ANOVA for experiment 1A showed a significant main effect of the display position on the RTs for the target-present condition ($F_{1,9} = 6.456$, $p = 0.031$), while neither the object tilt nor the interaction between the object tilt and the display position was found to be significant ($F_{1,9} = 2.788$, $p = 0.13$; $F_{1,9} = 0.165$, $p > 0.5$). The interaction between the display size and both or either of the other two factors was not significant.

In experiment 1B, both the display position and the object tilt had a significant main effect on RTs for the target-present condition ($F_{1,9} = 6.023$, $p = 0.037$; $F_{1,9} = 61.77$, $p < 0.0001$). The interaction between the display position and object tilt did not attain the level of significance ($F_{1,9} = 3.766$, $p = 0.08$). Since the interaction between the display size and the object tilt was significant ($F_{2,18} = 7.395$, $p = 0.005$), we performed two-way ANOVAs for the slopes of correct RTs against the display size. The results showed a significant effect for the object tilt ($F_{1,9} = 21.171$, $p = 0.0013$) and showed a nearly significant trend for the effect of the position ($F_{1,9} = 4.862$, $p = 0.055$).

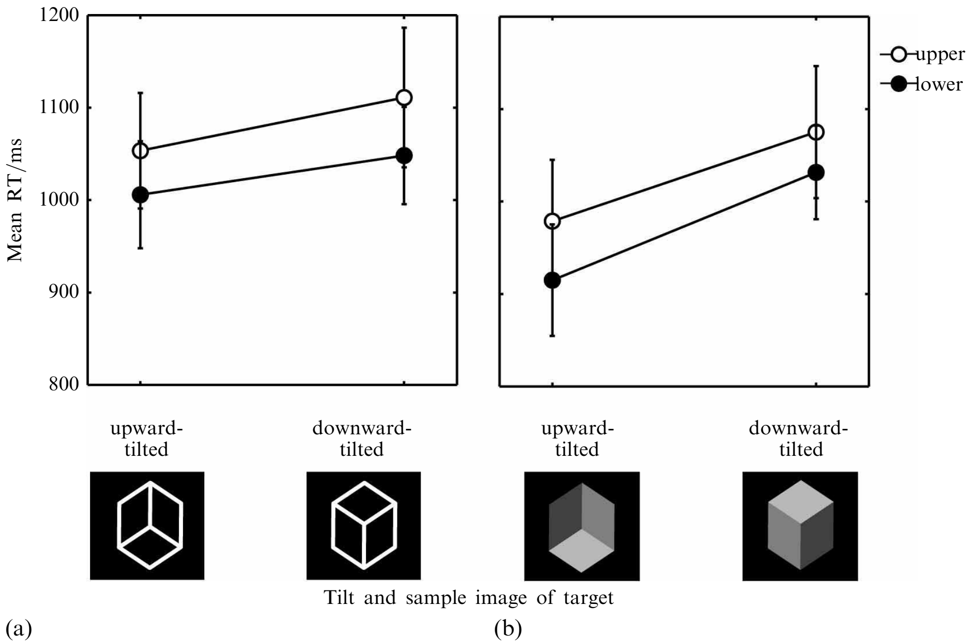

Figure 3. Mean correct reaction times for the target-present trials in (a) experiment 1A and (b) experiment 1B. The error bars represent SEM across subjects.

A significant main effect for the object tilt on the error rate was seen in both experiments 1A and 1B ($F_{1,9} = 6.824$, $p = 0.028$; $F_{1,9} = 9.466$, $p = 0.013$). These results indicate that the effect of display position and/or the object tilt was not the result of a trade-off between the speed and accuracy.

4.2 *Discussion of experiment 1*

The results of experiment 1 indicated that in both display positions the detection of an upward-tilted target among downward-tilted distractors was faster than that of a downward-tilted target among upward-tilted distractors. This implies that the top-view assumption was applied when objects were displayed not only in the lower position but also in the upper position.

Displaying the stimulus in the upper position only had a negative effect on the search performance in experiments 1A and 1B, even though the display position was not found to have any effect in the preliminary experiment. One possible reason is that the stimuli in experiment 1 might give the impression of 3-D objects being vertically aligned and floating in the air. Since this is an infrequent situation in our environment, the RTs for the upper-position condition were slower.

Another explanation for the performance deterioration is that different sensory systems might be dominant in the lower and upper positions. It has been suggested that an ambient extrapersonal system would be predominant when objects at a distance of 4.5 m are in the LVF, and an action extrapersonal system would be predominant when objects at that distance are in the UVF (Previc 1998). The construction of a stable 3-D mental representation is then considered to be one of the most important functions of the ambient extrapersonal mechanism, while an action extrapersonal system is responsible for providing a crude topographical representation. Therefore, it appears reasonable that the organisation and detection of 3-D objects is faster when the objects are in the lower position, whereas 2-D items, such as the stimuli used in our preliminary experiment, in the lower position offer no advantage. The remarkable effect of the object tilt in experiment 1B, which might correspond to increased three-dimensionality, can also be interpreted in terms of these models. These applications of the functional systems, however, are not certain; therefore, further research is necessary to confirm these speculations.

In experiment 1A, the RTs were longer than in experiment 1B; moreover, the search asymmetry between the two object tilts was not significantly different. Von Grünau and Dubé (1994) reported that the search performance became slower and the search asymmetry less pronounced as the impression of three-dimensionality was both weakened by the increasing stimulus size and strengthened by shading. Sun and Perona (1996) reported that the search of a field consisting of line-drawn parallelepipeds was much slower than that of a field consisting of shaded objects. These researchers argued that this was because they used a two-alternative forced-choice stimulus onset asynchrony paradigm with masking. However, our stimuli were not large compared to those in the other experiment and the procedure was the same as that in the experiments of von Grünau and Dubé (1994). We are of the opinion that in experiment 1A, the combination of the white lines and the black background might have weakened the 3-D impressions of the items and thereby made the search relatively slow and the search asymmetry between two object tilts less pronounced. A weak but continuing three-dimensionality is likely to result in a significant effect of the display positions discussed above.

A comparison of the RTs in experiment 1 with those in previous research that used similar stimuli and task revealed that our RTs were slower than those of von Grünau and Dubé (700 ms, 12 distractors, line objects) but faster than those of Previc and Naegele (1000 – 1100 ms, 11 distractors, shaded objects). Previc and Naegele argued that eye movements in their experiment caused the RTs to be longer than those in von Grünau and Dubé. Our experiment also permitted eye movements after the second fixation point disappeared, and this might be one of the reasons for the slow RTs in our experiments (1020 ms for experiment 1A, 918 ms for experiment 1B; 14 distractors, lower position, upward tilted) compared to those in von Grünau and Dubé.

In summary, the effect of viewing position did not replace the top-view assumption with a bottom-view assumption. However, there should be further examination whether it is impossible to use the information that one is viewing upward even when the stimulus has appropriate perspective information or/and light direction. Sun and Perona (1996) displayed the picture of a floor before displaying search fields that contained 3-D objects and found that this improved the search performance. They suggested that the background display might have served as a constant reminder that the stimuli should be given a 3-D interpretation and that perception was facilitated and the performance improved when the stimuli were consistent with the scene interpretation provided by the preceding display of background. If stimuli could provide an interpretation of 3-D objects hung from a ceiling by adding perspective information and/or lit-from-top information, the detection of a downward-tilted target among upward-tilted distractors at the upper position would be more efficient.

5 Experiment 2

In experiment 2, we added perspective information regarding the array of cube-like objects or/and changed the face colours of the objects in accordance with the top-lit assumption when they were viewed from the bottom. When the objects were displayed in an upper position, they could be interpreted as being lit from above and hung from a ceiling that is parallel to the ground (figure 4).

The stimuli for experiment 2A were generated by interchanging the lightness of the lightest and darkest faces of the objects used in experiment 1B. As a result, these objects presented the impression of being illuminated from the direction opposite to that from which the objects in experiment 1B were illuminated.

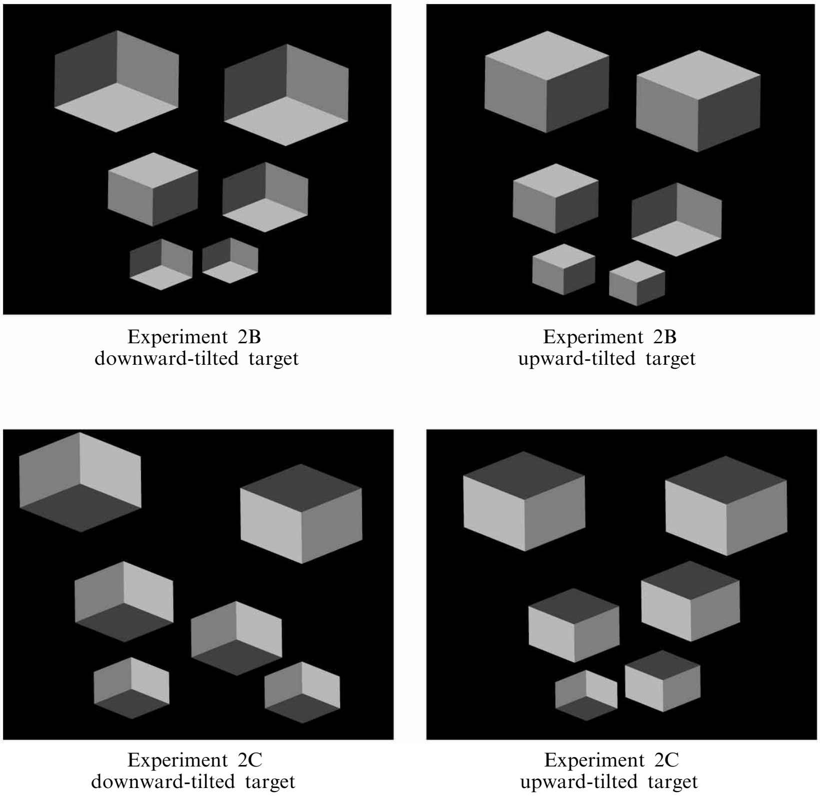

Figure 4. Examples of the stimuli used in experiment 2.

In experiment 2B, the size and arrangement of each of the items in the array contained perspective information, making them appear as being hung from a ceiling that was parallel to the ground. The origin of the projection was matched to the eye position of each subject. In order to prevent superimposition, the height of the 3-D objects was shorter than that of the objects in experiment 1. The average size of the search fields was nearly identical to those of experiment 1. The lightness of the object faces was the same as in experiment 1B. The stimuli for the upward-tilted target condition were generated by rotating each item in the downward-tilted target condition by 180° so that their arrangement and size of each item was identical in the downward-tilted and upward-tilted target conditions. These stimuli were used also in the lower-position condition, although at this position, the perspective information gave the impression that the objects were arranged on an oddly slanted plane. This is because we were especially concerned with determining whether there was a contextual effect facilitating the bottom-view assumption in this experiment.

The stimuli in experiment 2C included both changes in the face colour and the addition of perspective information.

Ten observers participated in experiment 2, of which eight had also participated in experiment 1. As in experiment 1, only one observer was aware of the experimental hypothesis.

5.1 *Results of experiment 2*

The results were analysed with a three-factor (display position, object tilt, display size) within-subjects ANOVA for the correct RT data in the present condition and the error rate for each of the experiments 2A, 2B, and 2C. The mean RTs are indicated in figure 5. The mean RTs as a function of display size and error rates for each stimulus condition (display position, object tilt) in experiment 2 are listed in table 2.

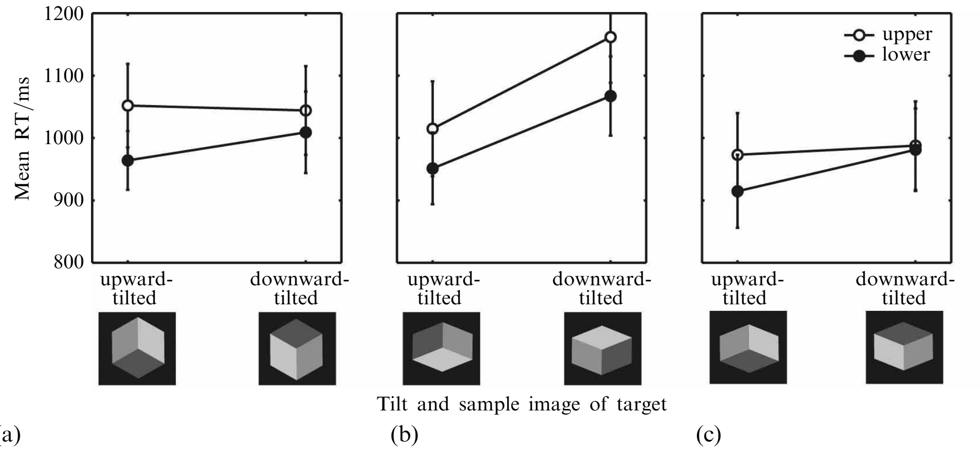

Figure 5. Mean correct reaction times for the target-present trials in (a) experiment 2A, (b) experiment 2B, and (c) experiment 2C. The error bars represent SEM across subjects.

Table 2. Reaction times as a function of the number of items for target-present trials and mean error rates in experiment 2.

Experiment	Position	Target tilt	Reaction time/ms			Error rate
			6 items	15 items	21 items	
2A	upper	upward	918	1059	1179	0.03
		downward	911	1100	1124	0.04
	lower	upward	868	970	1054	0.05
		downward	911	979	1137	0.04
2B	upper	upward	911	1031	1103	0.05
		downward	969	1120	1396	0.06
	lower	upward	890	922	1037	0.06
		downward	925	1068	1209	0.06
2C	upper	upward	867	981	1070	0.04
		downward	873	1019	1071	0.04
	lower	upward	805	953	990	0.03
		downward	838	1007	1100	0.04

The analysis of the RTs in experiment 2A revealed a significant main effect of the display position but not for the object tilt ($F_{1,9} = 5.554$, $p = 0.043$; $F_{1,9} = 0.335$, $p > 0.5$). The interaction effect between the display position and the object tilt did not attain the level of significance ($F_{1,9} = 4.659$, $p = 0.059$).

In experiment 2B, in which perspective information was added, both the main effects of the display position and the object tilt were found to be significant ($F_{1,9} = 13.314$, $p = 0.005$; $F_{1,9} = 69.296$, $p < 0.0001$). The interaction between the display position and the object tilt was not significant ($F_{2,18} = 1.49$, $p = 0.25$). These results were similar to those in experiment 1B, where upward-tilted targets and those in the lower position were detected comparatively faster.

The analysis of experiment 2C revealed a significant main effect for the position ($F_{1,9} = 11.877$, $p = 0.007$) but not for the object tilt ($F_{1,9} = 3.064$, $p = 0.114$). The interaction effect between the position and the object tilt was significant ($F_{1,9} = 6.726$, $p = 0.029$). Further analysis revealed that the effect of the object tilt was still significant in the lower-position condition ($p = 0.0168$) but not in the upper-position condition ($p > 0.5$).

A three-way ANOVA (display position, object tilt, display size) for the error rates in experiments 2A, 2B, and 2C did not show any significant effect for the display position and object tilt. These results indicate that the effect of the display position and/or the object tilt does not result from a trade-off between the speed and accuracy.

Moreover, we picked up the slopes of the maximum likelihood linear fit of the RTs as a function of display size for the target-present trials from experiments 2B and 2C. We conducted a supplementary analysis with the combined RT slope data using a three-way ANOVA (surface lightness, position, object tilt) to examine how the interchange of surface lightness affected search efficiency. Notable results from the analysis indicated a significant interaction between these three factors ($F_{1,9} = 5.664$, $p = 0.041$). Further analysis revealed a significant simple – simple main effect of the surface lightness only for the combination of the upper position and the downward-tilted target ($p < 0.0001$). However, a similar analysis for experiments 2A and 2C for examining the effect of the perspective information revealed no significant main effect and interaction. In addition, we selected the subjects who participated in both experiments 1B or 2A and conducted a similar analysis for the slopes. Although the interaction between these three factors did not attain the level of significance ($F_{1,7} = 5.416$, $p = 0.053$), we performed a follow-up analysis in order to examine the effect of the combination of the three factors. This revealed a significant simple – simple main effect of the surface lightness only for the combination of the upper position and the downward-tilted target ($p = 0.024$). Figure 6 indicates the search slopes in experiments 2 and 1B as a function of the replacement of surface lightness.

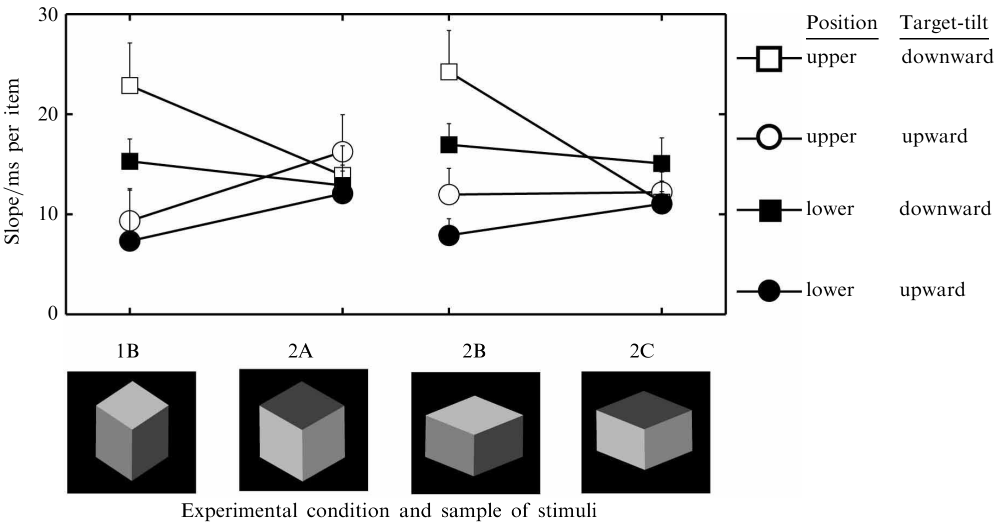

Figure 6. Mean slopes for the target-present trials in experiments 1B and 2A (left) and 2B and 2C (right). The error bars represent SEM.

5.2 *Discussion of experiment 2*

The main finding in experiment 2 was that the search asymmetry for the object tilt disappeared at the upper position when the appropriate perspective information and light direction were given. In experiment 2C, the interaction between the display position and the object tilt was significant, and the effect of the object tilt was significant only in the lower-position condition. We think this result indicates that it was possible for the visual system to use the information that the observer was looking upward for facilitating the visual-search task when the stimuli were consistent with being hung from a ceiling.

The disappearance of search asymmetry could be largely accounted for by the replacement of surface lightness rather than by the perspective information. Previous research has demonstrated that the replacement of surface lightness increases the efficiency regarding the organisation of upward-tilted cube-like stimuli (Enns and Rensink 1990; von Grünau and Dubé 1994). If the detection of the downward-tilted target is faster regardless of the stimulus position, this implies that only the replacement of surface lightness influences the increase in the search efficiency. In experiment 2C, however, the detection of a downward-tilted target was as fast as that of the upward-tilted target in the upper position but continued to be slow when it was in the lower position; this implies that the effect of the replacement of surface lightness was pronounced in the upper position. In experiment 2A, a relatively smaller but similar effect was also observed.

The results of experiment 2 can be understood as indicating that information regarding the viewing direction can modulate the visual system to facilitate the detection of a downward-tilted target among upward-tilted distractors. This facilitation resembles the contextual effects reported by previous researchers (Sun and Perona 1996; McCarley and He 2001). Sun and Perona (1996) suggested that the top – down expectation effects are likely to facilitate scene interpretation when the stimuli are consistent with the scene interpretation. In their experiments, the background display of the receding plane could have served as a constant reminder that the stimuli should be given a 3-D interpretation. In our experiments, the expectation of the view-from-below could be strengthened by displaying the stimulus in the upper position. Moreover, only when the stimuli were consistent with the expected scene, did the detection of the downward-tilted targets become faster in the upper position. McCarley and He (2001) examined the effects of sequential priming on the perceptual organisation of 3-D displays of globally receding top-visible surfaces and globally receding bottom-visible surfaces. They found that the search became faster when the 3-D stimulus orientation remained unchanged in consecutive trials, indicating the existence of substantial sequential priming by 3-D stimulus layout. This effect was seen against both ground-like and ceiling-like planes. In our opinion, their results demonstrate that the visual system uses extraretinal information for organising a 3-D environment, and our results indicate that this organisation is facilitated by information regarding one's viewing direction and/or the stimulus position.

It could be assumed that the results of these experiments reflected a bias of performance strategy—in other words, the observers explicitly expected upward-tilted distractors when the stimuli were displayed in the upper position. However, it appears to be implausible that observers were prepared to respond only to the stimuli with a downward-tilted target displayed in the upper position in experiments 2C and 2A because our subjects were unaware of the aim of our experiment. Moreover, in experiment 2B, poor performance was obtained even with a downward-tilted target in the upper position. Therefore, we believe that the benefit of viewing direction was achieved only for a set of stimuli consistent with the positional information.

Adding perspective information appears to have a weaker effect than interchanging the surface lightness. In experiment 2B, the display position and the object tilt were found to have significant main effects, and these effects were nearly identical to those in experiment 1B. We speculate that the visual system uses the perspective information supplementally and that such information has an effect only when combined with information regarding the appropriate light direction. Sun and Perona (1996) reported that perspective information without a floor context impaired the visual-search performance, while perspective information with a floor context improved it. Our results are in accordance with these results in that perspective information might promote the organisation of 3-D objects only when it is displayed with other information.

The stimuli in experiments 2B and 2C formed an oddly slanted plane at the lower position. For a proper understanding of our results, it is necessary to examine the manner in which this incongruent information affected search performance. Therefore, we separated the lower-position conditions in experiment 2C, which include the incongruent perspective information, and compared them with corresponding conditions in experiment 2A. A three-way ANOVA (existence of inconsistent perspective information, object direction, and display size) against the mean RTs for the lower-position condition in experiments 2A and 2C revealed that the existence of inconsistent perspective information had no significant effect on the RTs ($F_{1,9} = 0.195$, $p > 0.5$) and interaction effects between object tilt ($F_{1,9} = 0.248$, $p > 0.5$). These results indicate that even though the perspective information was presented in an irregular form, it had little effect on our experiments.

However, there remains the possibility that this weakness of perspective information could have resulted from the stereoscopically frontoparallel search field. Although our subjects did not report that they perceived the search field as being completely flat, the stereoscopically frontoparallel display could have interfered with the organisation of the bottom-away plane implicated by changes in item size. This could have given rise to the relatively weak effects of perspective information.

Although shading information strongly influenced the detection of downward-tilted targets, the performance for an upward-tilted target among downward-tilted distractors continued to be efficient even when the shading and perspective information were contextually incongruent with the display position. The mean RT for the upward-tilted targets in the lower position was shorter than those of all the other conditions in experiment 2C. These results indicate that the top-view assumption is relatively strong.

6 General discussion

We examined here the effect of stimulus position in external space on the use of a viewpoint-related assumption. According to one extreme hypothesis, we expected that the information that one's view is directed upward might facilitate the detection of a downward-tilted target among upward-tilted distractors, which would be contrary to the previously reported top-view assumptions. Our results confirm this hypothesis to be false because an upward-tilted object among downward-tilted distractors was rapidly detected in most of the experiments. However, when the visual system provided the information that the viewing direction was upward and when the shading and perspective information were consistent with the viewing direction, a downward-tilted target among upward-tilted distractors was detected with nearly the same efficiency as an upward-tilted target among downward-tilted distractors.

This benefit for organising upward-tilted distractors largely depended on the top-lit assumption; it depended on the perspective information to a slight extent. However, the top-view assumption remained unaffected by experimental variables such as the display position, surface lightness, and perspective information. We assume this to be because the top-view assumption is embedded in the visual system, and therefore the visual system cannot change it. The visual system might require access to a higher stage of visual processing in order to promote the detection of downward-tilted targets among upward-tilted distractors. We believe that limiting the conditions for achieving the contextual effect would be appropriate for the visual system because responding to too many situations is likely to deprive the human visual system of its efficiency.

Our results were similar in several aspects to those of von Grünau and Dubé (1994), which were obtained in the examination of the visual-field anisotropy of the search asymmetry with regard to object tilt. This effect was relevant to cases in which the information regarding the illumination direction was appropriate (experiment 4, von Grünau and Dubé 1994). This similarity raises the question whether the observers' eye directions were appropriately controlled in the present experiments. If the observers captured the stimuli in their UVF when the stimuli were in the upper position and in their LVF when the stimuli were in the lower position, the obtained results merely replicated the visual-field effects reported by von Grünau and Dubé. Although we did not monitor eye movements, the head directions of observers were carefully controlled and the stimulus was not presented unless the subject moved his head as instructed. Moreover, the search efficiency in the UVF averaging the upward- and downward-tilted target conditions appeared to be constant between the top-lit shading and inconsistent shading conditions in von Grünau and Dubé. However, in this study, the search efficiency in our experiment 2C (top-lit shading) was higher than that in experiment 2B (inconsistent shading). This could suggest that the effect of consistent shading and perspective information against the downward-tilted target condition in the upper position was more effective in our experiments.

Conversely, the results of von Grünau and Dubé are likely to be largely due to the contextual effects described in this paper, but not to the functional differences in the visual field. Previc and Naegele (2001) reported that the visual search for upward-tilted cubes located in the UVF was faster than for those in the LVF. They suggested that these results were due mainly to biased search mechanism. Their results contradict those of von Grünau and Dubé in which the visual search in LVF was faster. However, there were several differences in the experimental settings between these two earlier reports. In particular, von Grünau and Dubé displayed the fixation point above or below a search field in their experiment 4. Previc and Naegele, however, displayed the fixation point in the centre, similar to our experiments. Here, we speculate that the object position relative to the eye direction could have caused the contextual effect in experiment 4 of von Grünau and Dubé and the contextual effect overrode the advantage of the biased search mechanism for the UVF. However, further studies are required to examine whether the same phenomenon was investigated in von Grünau and Dubé and the present study.

In this research, we controlled the display position of stimuli as an experimental variable. However, we were unable to determine the types of information which are most effective for facilitating the detection of a downward-tilted target at the upper position, such as the display position itself or information regarding the rotated head angles acquired from efferent signals during head movement. It would be interesting to investigate the relative strength of different cues in supporting a contextual effect. For example, an experiment with a large system that can hold an observer's body in a tilted position can be conducted to determine whether head orientation or body orientation is more effective. Furthermore, controlling the temporal interval between a head movement and a stimulus onset will help determine whether efferent signals related to head movements act as the necessary input.

References

Attneave F, 1954 "Some informational aspects of visual perception" *Psychological Review* **61** 183 – 193

Barlow H B, 1961 "Possible principles underlying the transformation of sensory messages", in *Sensory Communication* Ed. W A Rosenblith (Cambridge, MA: MIT Press) pp 217 – 234

Enns J T, Rensink R A, 1990 "Influence of scene-based properties on visual search" *Science* **247** 721 – 723

Enns J T, Rensink R A, 1991 "Preattentive recovery of three-dimensional orientation from line drawings" *Psychological Review* **98** 335 – 351

Gregory R, 1970 *The Intelligent Eye* (New York: McGraw-Hill)

Grünau M von, Dubé S, 1994 "Visual search asymmetry for viewing direction" *Perception & Psychophysics* **56** 211 – 220

Hill H, Bruce V, 1993 "Independent effects of lighting, orientation, and stereopsis on the hollow-face illusion" *Perception* **22** 887 – 897

Hill H, Bruce V, 1994 "A comparison between the hollow-face and 'hollow-potato' illusions" *Perception* **23** 1335 – 1337

Johnston A, Hill H, Carman N, 1992 "Recognising faces: effects of lighting direction, inversion, and brightness reversal" *Perception* **21** 365 – 375

Kleffner D A, Ramachandran V S, 1992 "On the perception of shape from shading" *Perception & Psychophysics* **52** 18 – 36

Langer M S, Bülthoff H H, 2001 "A prior for global convexity in local shape-from-shading" *Perception* **30** 403 – 410

McCarley J S, He Z J, 2000 "Asymmetry in 3-D perceptual organization: ground-like surface superior to ceiling-like surface" *Perception & Psychophysics* **62** 540 – 549

McCarley J S, He Z J, 2001 "Sequential priming of 3-D perceptual organization" *Perception & Psychophysics* **63** 195 – 208

Marr D, 1982 *Vision* (San Francisco, CA: W H Freeman)

Previc F H, 1998 "The neuropsychology of 3-D space" *Psychological Bulletin* **124** 123 – 164

Previc F H, Naegele P D, 2001 "Target-tilt and vertical-hemifield asymmetries in free-scan search for 3-D targets" *Perception & Psychophysics* **63** 445 – 457

Ramachandran V S, 1988 "Perception of shape from shading" *Nature* **331** 163 – 166

Ramachandran V S, 1989 "Interactions between motion, depth, color and form: the utilitarian theory of perception", in *Vision: Coding and Efficiency* Ed. C Blakemore (Cambridge: Cambridge University Press) pp 346 – 360

Reichel F D, Todd J T, 1990 "Perceived depth inversion of smoothly curved surfaces due to image orientation" *Journal of Experimental Psychology: Human Perception and Performance* **16** 653 – 664

Sun J Y, Perona P, 1996 "Preattentive perception of elementary three-dimensional shapes" *Vision Research* **36** 2515 – 2529

Treisman A Gormican S, 1988 "Feature analysis in early vision: evidence from search asymmetries" *Psychological Review* **95** 15 – 48

Treisman A, Souther J, 1985 "Search asymmetry: a diagnostic for preattentive processing of separable features" *Journal of Experimental Psychology: General* **114** 285 – 310

Wexler M, Panerai F, Lamouret I, Droulez J, 2001 "Self-motion and the perception of stationary objects" *Nature* **409** 85 – 88

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION
VOLUME 36 2007

www.perceptionweb.com