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The Magnitude of Binocular Disparity Modulates Search Time for Targets Defined by a Conjunction of Depth and Colour

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Nakayama and Silverman (1986) proposed that, when searching for a target defined by a conjunction of color and stereoscopic depth, observers partition 3D space into separate depth planes and then rapidly search each such plane in turn, thereby turning a conjunctive search into a "feature" search. In their study, they found, consistent with their hypothesis, shallow search slopes when searching depth planes separated by large binocular disparities. Here, the authors investigated whether the search slope depends upon the extent of the stereoscopically induced separation between the planes to be searched (i.e., upon the magnitude of the binocular disparity. The obtained slope shows that (1) a rapid search only occurs with disparities greater than 6 min of arc, a value that vastly exceeds the stereo threshold, and that (2) the steepness of this slope increases in a major way at lower disparities. The ability to implement the search mode envisaged by Nakayama and Silverman is thus clearly limited to large disparities; less efficient search strategies are mandated by lower disparity values, as under such conditions items from one depth plane may be more likely to "intrude" upon the other.

Keywords: visual search, conjunctive search, stereoscopic depth, color

Stereoscopic depth is often included amongst the basic dimensions of the visual scene that may be preattentively available and that can be used for a rapid allocation of attention to the various elements of a visual scene, thereby enabling efficient search strategies (e.g., Wolfe, 2000; Wolfe & Horowitz, 2004).

In a series of studies, Nakayama and colleagues (He & Nakayama, 1992; Nakayama & He, 1995; Nakayama & Silverman, 1986) proposed that an observer engaged in a visual search task which requires the use of binocular depth cues can use such cues to segregate visual information in three-dimensional (3D) space into a series of separate surfaces that can then be rapidly searched one at a time as needed. Consider a search for a target defined by a conjunction of stereoscopic depth and colour, in which the observer is presented with two depth planes (see Figure 1). Nakayama and Silverman (1986) presented blue squares on the depth plane that appeared to be closer to the observer, and red squares on the depth plane that appeared farther away; the target of the search was either a single blue square amongst the red squares or a single red square amongst the blue squares. They suggested that the participants first searched, say, the depth plane containing the blue items for a red square and, if the target was not found, searched next the depth plane containing the red items for a blue square. By so doing, the observers in effect "deconstructed" a nominally "conjunctive" search—which is as such typically time consuming into two colour-based "feature" searches, which are, in general, carried out rapidly (e.g., Treisman & Gelade, 1980). In line with this interpretation, their observers' response times on target present trials resembled those typically produced by two successive feature searches, rather than those induced by a conjunctive target. Additional experiments provided additional support for their hypothesis of an early decomposition of 3D visual information into depth planes or surfaces (He & Nakayama, 1992; Nakayama & He, 1995).

These researchers' formulation of this hypothesis in categorical terms may lead one to assume that the search behaviour they postulate is enabled as long as the separation between these surfaces exceeds the observer's threshold for registering relative distance by means of binocular cues. However, in all of the above studies, Nakayama and colleagues used only very large binocular disparities (≥15 min of arc) to separate the depth planes. Accordingly, a significant theoretical statement about the human visual system's ability to parse 3D space into a number of independent surfaces for the purpose of efficient search performance is de facto based upon very narrow empirical foundations. In actuality, we simply do not know whether, in their task, the search strategy they envisaged can be implemented for all disparities that are clearly above an observer's stereo threshold.

There are reasons to suspect that the ability to parse the 3D visual scene into different depth planes may become more difficult as the separation between the depth planes is reduced. In particular, for disparities clearly above threshold but less than the 15 min of arc used by Nakayama and Silverman (1986), it could be that the information presented on one plane may intrude, or be confused with, information presented on a nearby plane. Some studies support this possibility. Andersen and Kramer (1993) had participants search for a target that was presented on one plane with two "distractors" (which flanked the target along the horizontal axis) presented on a different plane. They found that the distractors interfered with the target for both crossed and uncrossed disparities

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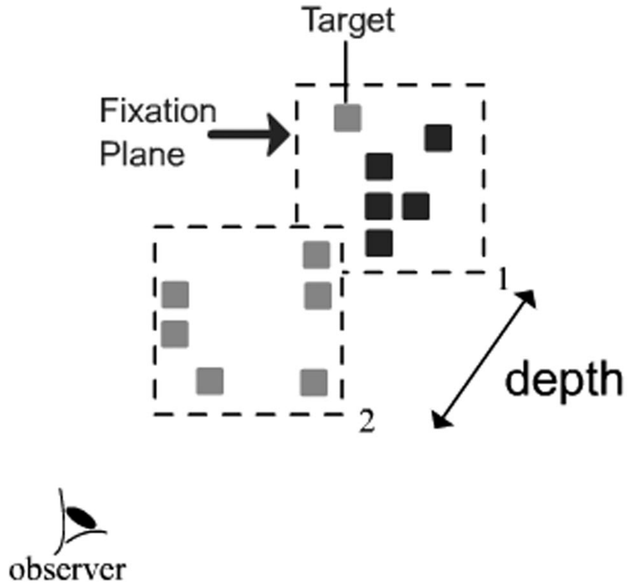

Figure 1. Schematic representation of the search displays used in the experiment. All the planes not on fixation appeared on crossed disparity (depth plane that is labeled "2"). The distractors consisted of green squares (here depicted in grey) appearing in the front, and of red squares (here depicted in black) appearing in the back. In this example, a target is present (the target is a "green" square that appears in the back).

when the separation between the target's plane and the distractors' plane was less than 4 min of arc. Their results further suggested that the supposed interference gradually decreased with increasing disparity (see also Andersen, 1990).

The relationship between the size of the disparity and search efficiency, however, is not one that can be straightforwardly predicted. For instance, O'Toole and Walker (1997) found that a search for a single square that was presented on a plane that was 4 min of arc—hence well above stereo threshold—in front of a depth plane filled with other squares was "inefficient." This result is somewhat surprising, since stereo-depth is amongst the features that can be preattentively processed and thereby used to guide visual attention efficiently to the target location (e.g., Wolfe, 2000; Wolfe & Horowitz, 2004). Hence, a task such as the one used by these researchers should have produced an efficient search. Conversely, as noted, Nakayama and Silverman obtained results that point to an efficient search with a conjunctively defined target, but with a much larger disparity. In addition, Theeuwes, Atchley, and Kramer (1998), who investigated the spatial distribution of visual attention in 3D space, found that distractors interfered with the target when target and distractors were spatially separated in depth by as much as 25 min of arc (with both crossed and uncrossed disparities).

Taken together, these results suggest that the size of the binocular disparity is an important and as yet ill understood determinant of visual performance in search tasks. In particular, it is clearly premature to categorically claim that observers can turn a conjunctive search into sequential feature searches of two depth planes in absence of a more thorough investigation of the impact of the size of the relative disparity on this task.

The primary purpose of the present study was to determine how the magnitude of the disparity between two depth planes affects performance for a target defined by a conjunction of colour and stereoscopic depth in tasks such as those employed by Nakayama and coworkers. We hypothesised that the segregation of visual information into depth planes that appears to enable the rapid search of these displays with large disparities may be more difficult to implement as the disparity between the depth planes decreases. We sought to test this hypothesis by employing a search task very similar to that described by Nakayama and Silverman (1986) in which observers searched for a target defined by a conjunction of colour and depth. However, instead of observing performance at only one large disparity, we measured it as a function of several levels of crossed disparity, ranging from 1 to 16 min of arc.

To determine the efficiency of search performance at each disparity tested, we varied the number of distractors on each of the two planes and determined the slope of the function relating response time to the number of distracting items. A more efficient search should produce a lower slope and shorter mean response time than a less efficient search. By observing how the degree of disparity affected the slope of the function relating response time to the number of distracting items, we hoped to determine whether the search strategy postulated by Nakayama and colleagues became readily available as long as the stereo threshold was exceeded, or whether the observer's search strategy shifted - whether incrementally or in more discontinuous fashion—from a less efficient search strategy (steeper slopes and longer mean response times) to more efficient search strategy (shallow slopes and lower mean response times) as disparity increases.

Method

Participants

Twenty young undergraduate students at the University of Toronto in Mississauga participated in this study. They were either paid volunteers or served in the study in partial fulfillment of the requirements for an introductory psychology course. Ten participants were tested with disparity levels of 1, 2, 3, and 4 min of arc; 10 others with disparity levels of 4, 8, 12, and 16 min of arc.

All the participants were unacquainted with the research carried out in our labouratory. Their visual acuity was measured with Snellen charts, and was in all cases at least 20/25 or better, both monocularly and binocularly. Stereoscopic depth thresholds ($M =$ 30.42 sec of arc), assessed with the Frisby Stereotest, were for all participants considerably lower than the smallest value of binocular disparity used in the experiment. The experiment was conducted in compliance with University of Toronto guidelines for the conduct of research with human participants.

Apparatus and Stimuli

The stimuli were generated by programming a PC-based visual stimulus generator (VSG) graphics card from Cambridge Research (Kent, UK), and were displayed on a Sony (Tokyo, Japan) 17SE2T TV colour monitor with a refresh rate of 130 Hz and a spatial resolution of 1024 × 768 pixels. The monitor's luminance was gamma-corrected before each session. The observers perceived stereoscopic depth by wearing ferro-electric FE-1 shutter goggles from Cambridge Research synchronised with the alternating TV frames at the rate of 65 Hz per eye. A head and chin rest was used to minimise head movements and to help maintain fixation at a viewing distance of 165 cm. A CB2 response box from Cambridge Research was used to collect the responses of the participants. An additional independent processor on the VSG card measured response time (RT).

The display spanned $4.5^\circ \times 4.5^\circ$ of visual angle, and occupied the central portion of the TV monitor. The distractor items consisted of red and green squares (luminance = 8.2 cd/m^2) and were presented on the darkened display (luminance: 0.181 cd/m^2). The squares each subtended 10×10 min of arc. Red and green squares were presented on two separate planes, each structured as an invisible 8×8 grid, which ensured that the horizontal and vertical spacing between any two adjacent squares was constant at 27.5 min of arc. The red distractor squares were assigned to the grid that was always presented with zero disparity, that is, at fixation. The green distractor squares were assigned to the grid that was randomly presented with a crossed disparity of 1, 2, 3, 4, 8, 12, or 16 min of arc (depending on the disparity range administered to an observer as described above); hence, these green squares always appeared to be located on a plane in front of the fixation plane. On each trial, the display consisted of 12, 30, or 48 squares (the number of these items shall be referred to henceforth as “set size”). The target was either a green square amongst the red squares, or a red square amongst the green squares (see Figure 1); the target was presented on half of the trials. Number of squares per plane, frequency of occurrence of the target on a plane, and target presence for a particular set size were counterbalanced across trials; each of the disparity levels administered to a participant were presented during each block of trials, in a random order.

Procedure

The participants were first verbally instructed about their task, and were then administered a block of 144 practise trials on their first session; these data were discarded. They were instructed to produce a response that was as rapid as possible whilst maintaining a high level of accuracy, around 80% to 90% correct. A block of trials consisted of 2 target-presence conditions (present and absent), 3 set sizes (12, 30, and 48 squares), and four disparity levels (either 1, 2, 3, and 4 min of arc or 4, 8, 12, and 16 min of arc depending upon the participants being tested). Each of these combinations was presented 6 times for a total of 144 trials per observer. Each participant was administered 6 such blocks, for a total of 864 trials.

Each observer was admitted to the darkened testing chamber, and was given ample time to adjust to the dark surroundings before sitting in front of the apparatus. The onset of an experimental trial was signaled by the presentation of a small white fixation cross in the middle of the blank monitor screen. The observer fixated upon the cross and pressed the middle one of a three-button response box when ready to begin. After pressing the button, the fixation cross remained on for 450 ms to allow the participants to reposition their fingers onto the left and right buttons. The disappearance of the fixation cross was followed by a 350-ms blank screen, to minimise possible forward masking effects. The search display was then continuously presented, until the observer produced a response. The observer’s task was to press the left button on the response box, when the display appeared to contain the target; otherwise, the observer was instructed to press the right button on the same box. Incorrect responses were followed by a brief 500 Hz feedback tone. After the response was given, the blank screen with the fixation cross reappeared, thereby signaling the onset of a new trial. Upon completion of each block of trials the participants were informed about their average response times and accuracy level.

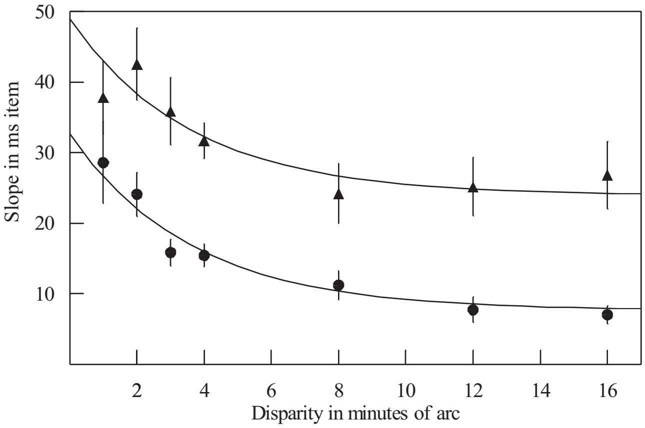

Figure 2. Search slope values for each disparity level and target condition [target present (●) and target absent (▲)]. The fitted lines represent the best fitting exponential decay functions described in the text. Bars indicate the *SE*.

Results and Discussion

We determined, for each participant at each disparity level, the slope of the line relating response time to set size (the search slope) using the method of least squares. To determine whether performance at a disparity level of 4 min of arc was affected by the range of disparities encountered by the participants, we compared the 4 min of arc search slopes for the group administered the 1 to 4 min of arc disparities with the corresponding search for the group administered the 4 to 16 min of arc disparities. The search slopes of the two groups did not differ at a disparity of 4 min of arc, $t(18) = -1.48$, $p = .155$; hence, we collapsed the data across the 20 participants for the search slope analysis at 4 min of arc. The results of the experiment, summarised in Figure 2, show that performance depends on the disparity value used to produce the two depth planes. On target-present trials, search slopes decrease with increasing disparity. Bonferroni corrected *t* tests show that all slopes except for the two largest disparities are significantly different from zero ($p > .05$). These slopes drop from about 28.58 ms/item in the 1 min of arc condition to about 7.01 ms/item in the 16 min of arc condition. Similarly the mean RT decrease with increasing disparity (see Figure 3). The Tukey post hoc test revealed that the mean response times at 1 arcmin and 2 arcmin disparity levels were significantly different from each other and significantly different from the mean response times at all other disparity levels. On target absent trials, the slopes show a similar decrease; however, they are about 10 ms/item higher than the slopes obtained with the target. Bonferroni corrected *t* tests show that all slopes are significantly different from zero ($p > .05$). A Tukey post hoc test suggested that the mean RT of the 1 arcmin disparity level was significantly larger compared to all other mean

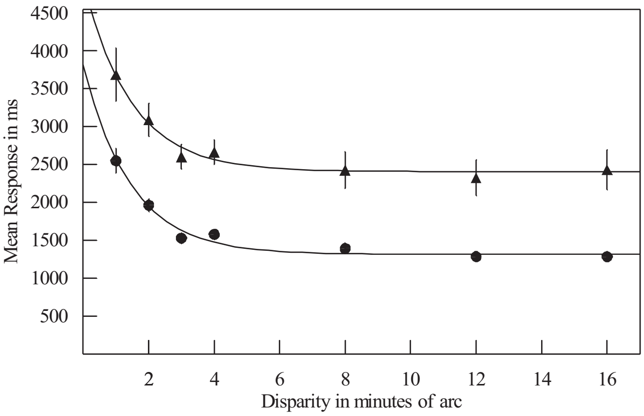

Figure 3. Mean response time (RT) as a function of binocular disparity and target condition [target present (●) and target absent (▲)]. The fitted lines represent the best fitting exponential decay functions described in the text. Bars indicate the *SE*.

RT except for the mean RT of the 2 arcmin condition. No other mean RTs were significantly different (for mean RT see also Table 1). To investigate the effect of disparity on search efficiency more quantitatively, we described the relationship between disparity and search slopes with an exponential decay function:

$$\text{slope} = B + \text{A}^{*}\text{e}^{-\text{k}^{*}\text{disparity,}}$$

where B is the asymptotic value that the slope approaches as disparity increases, ($B + A$) represents the slope value at zero disparity, and k the decay rate. We fit the functions for both target present and target absent first assuming independent values for A, B, and k for both functions (a six parameter fit to two functions: A_{present}, B_{present}, k_{present}, A_{absent}, B_{absent}, k_{absent}), and then identical values of A and k for both present and target absent conditions (a four parameter fit to two functions: A, k, B_{present}, B_{absent}). Because the six parameter fit accounted for only a 0.7% increase of the amount of variance accounted for over the four parameter fit (96.0% for six parameters vs. 95.3% for four parameters), the four parameter fit is shown in Figure 2 ($A = 25.02$, $k = 0.2765$, $B_{\text{present}} = 7.626$, $B_{\text{absent}} = 23.95$).

As with the search slopes we did not find any significant difference of mean response time (RT) at 4 min of arc between the two groups of participants (1–4 min of arc and 4–16 min of arc): $t(18) = 1.95$; $p = .067$. Accordingly, we collapsed the data across all participants for the mean RT analysis at this level of disparity and fit a four-parameter exponential function to the data (both the four parameter and six parameter functions fit the data approximately equally well, accounting for 99.1% of the total variance). The fitted parameters were as follows: $A = 2506$, $k = 0.6897$, $B_{\text{present}} = 1311$, $B_{\text{absent}} = 2406$. Figure 3 shows that a four-parameter exponential model provides a good fit to the average response times. Note, however, that the average response time decays more rapidly with disparity and approaches its asymptote more quickly than does the equivalent function for slopes of the search function (compare Figures 2 and 3).

Figure 4 plots average error rate as a function of disparity, along with the fit of the exponential model ($A = 82.19$, $k = 1.298$, $B = 5.590$). Again the exponential model provides a good fit to the data, accounting for 98.9% of the total variance in error rate. However, the exponential function declines at a faster rate and approaches its asymptotic value more quickly than either of the functions relating slopes to disparity or mean reaction time to disparity.

To obtain rough estimates of when the exponential functions for slopes, mean reaction time, and error rate reach their asymptotic

Table 1
Mean Reaction Time (RT) and Mean Error Rates Along With the Respective SE*s Listed for Each Target Level, Disparity, and Set-Size Separately*

		Target present				Target absent			
Disparity	Set size	Mean RT (ms)	*SE* of mean RT	error %	*SE* of error	Mean RT (ms)	*SE* of mean RT	error %	*SE* of error
1	12	1989.38	59.52	16.5	3.94931	2602.32	64.972	29.7222	3.49038
	30	2634.04	93.479	16.1667	3.72352	3589.37	88.693	40.2778	4.04133
	48	3052.62	119.382	20.0555	4.09041	3993.31	101.616	45.2778	5.64815
2	12	1528	35.82	5.6111	1.53927	2052.96	40.841	13.9444	2.96348
	30	1919.52	51.619	4.5	2.03274	2853.88	46.554	16.6667	3.56211
	48	2413.62	76.603	1.9445	1.17487	3510.28	69.471	29.2778	2.93745
3	12	1230.18	21.042	1.9445	0.72318	1636.32	31.476	3.3334	1.15648
	30	1548.79	36.587	0.6111	0.40951	2371.55	42.577	9.2778	1.46997
	48	1804.36	42.773	0.8333	0.59289	2714.19	46.76	21.0556	3.33174
4	12	1294.92	19.567	3.4722	1.95252	1728.4	28.624	4.5834	0.95111
	30	1570.78	28.677	3.0833	1.5334	2447.72	38.131	10.4167	1.55935
	48	1849.57	40.591	1.6667	0.99544	2906.72	43.133	21.4445	2.09714
8	12	1184.59	21.329	0.5556	0.37037	1570.04	29.594	3.8889	1.03107
	30	1393.73	35.374	0.5556	0.37037	2146.11	44.715	12.7778	2.72165
	48	1596.22	47.339	0.5556	0.37037	2397.2	53.9	19.7222	2.88229
12	12	1140.23	21.339	0.8333	0.42432	1529.91	31.169	3.6111	1.43742
	30	1301.09	30.2	0.8333	0.42432	1926.81	44.78	7.7778	1.64596
	48	1424.7	38.168	0.2778	0.27778	2280.11	46.486	16.3889	2.56767
16	12	1143.45	22.29	0.5556	0.37037	1492.5	32.752	4.1667	1.18937
	30	1295.74	29.212	0.2778	0.27778	1947.06	40.241	8.8889	1.97723
	48	1400.47	38.067	0.2778	0.27778	2238.35	46.645	15.2778	2.03914

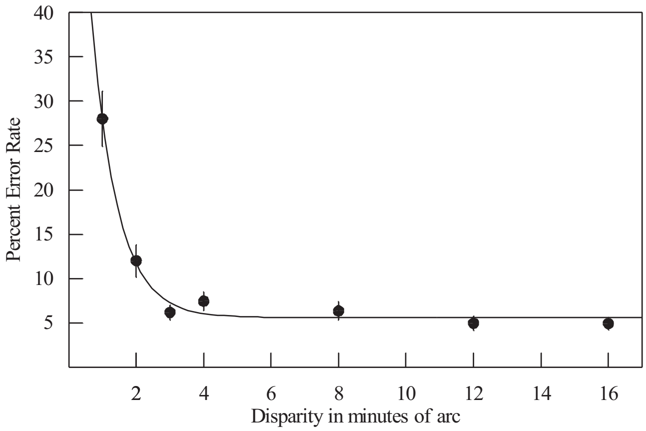

Figure 4. Percent errors as a function of binocular disparity for the combined target present and target absent trials. The fitted line represents the best fitting exponential decay function described in the text. Bars indicate the *SE*.

values, we also fit a two-state model to the data in which we assumed that the dependent variable, *y*, decreased linearly with the disparity until the disparity value was equal to b, and then remained constant thereafter, that is, we fit the model

$$y_{present} = m^{*}(x - b) + c_{present},$$

$$0 < x < b y_{present} = c_{present},$$

$$b < x < \infty y_{absent} = m^{*}(x - b) + c_{absent},$$

$$0 < x < b$$

to the data in Figures 2 through 4. This model provides an approximate estimate, *b*, of where the exponential function reaches its asymptotic value. The values of *b* were 2.38, 4.24, and 5.79 min of arc for y = error, mean response time, and search slopes, respectively. It is also interesting to note that these two-state functions provide a slightly better fit for error and slopes than the corresponding exponential functions, but not for mean reaction times.

A comparison of Figures 4 and 2 indicates that the error function reaches its asymptotic value at a much lower disparity value than does the search slope. No further improvements in accuracy are observed once the disparity value reaches 3 min of arc. The search slope, however, continues to decline up to at least 6 min of arc. Hence, observers are able to perform the task at asymptotic levels of accuracy well before they can perform it efficiently (shallow search slopes of about 10 ms/item on target present trials are usually taken as an indication that the presence of the target can be quickly ascertained regardless of set size, as is typically the case with "feature" searches: e.g., Wolfe, 1998).

A possible reason why the asymptote for error rate is reached at a smaller disparity value than that found for search slope is that even though two planes may become perceptually distinct at relative small disparities, it still may be the case that information from one depth plane sometimes intrudes upon the other (a "fuzzy boundary" concept for depth planes). For example, suppose the target was a red square amongst the green squares constituting the closest depth plane. If some of the red squares that constituted the further depth plane "intruded" into the closest depth plane consisting of green squares, the observer might see more than one red square amongst the green squares constituting the nearest depth plane. If this occurred the observer would then have to examine each region locally to determine if the red square in that region was really on the closest depth plane. Hence, the search would not be as efficient. However, as the depth planes become more distant, the likelihood of intrusions diminishes, and the search becomes more efficient. Finally, at some point, the likelihood of intrusions becomes so small that further increases in disparity lead to negligible increases in search efficiency. In other words, observers can only use the efficient search strategy when the disparity between the two depth planes is large enough to preclude an object from one depth plane from intruding into another.

Figure 3 shows that mean reaction time, which is often taken to be a measure of task difficulty, reaches its asymptotic value when the disparity starts to exceed 4 min of arc. This suggests that task difficulty does not change beyond this disparity value; yet, search slopes continue to decline between 4 and 7 min of arc. Hence, search efficiency continues to decline beyond the point where task difficulty has reached its asymptote. This fact militates against the view that declines in search slopes merely reflect declines in task difficulty, because if task difficultly was solely responsible for the changes in search slopes, we would expect the function for search slopes to asymptote at approximately the same disparity value as it does for mean reaction time. We argue, in conclusion, that, in the kind of task originally investigated by Nakayama and Silverman, the observer needs a separation of about 6 to 7 arcmin to minimise intrusions of objects from one plane onto another, so that a more efficient search strategy can be effective.

Our results, in sum, both corroborate and qualify the validity of the hypothesis originally proposed by Nakayama and Silverman (1986). The search behaviour they envisaged with their displays can only occur when binocular disparity exceeds a minimum, fairly large value. This value corresponds to a rather large spatial separation of two depth planes of at least 5.8 cm when a viewing distance of 50 cm is assumed. Other, less efficient search strategies may be required of the observer when the level of disparity is such that, although it permits a rough segregation into two planes, there is still some intrusion of information from one plane onto another. In other words, when the fuzzy borders of the two planes overlap, observers must employ a more detailed and less efficient search strategy.

Our results may also help solve a seeming incongruity in the research literature already noted: namely, that a feature search with stereoscopic depth is inefficient (O'Toole & Walker, 1997) whilst a conjunctive search with stereoscopic depth as one of the features is efficient. Our data suggest that search efficiency between the two studies differed because of the different amounts of disparity they employed. In their feature search, O'Toole and Walker used a disparity of 4 min of arc to separate a target from the distractors, whereas Nakayama and Silverman used a much larger disparity (about 20 arcmin) in their conjunctive search task. If Nakayama and Silverman had tested their conjunctive search with a disparity of 4 min of arc, they might have found, as we have here, an inefficient search. Conversely, O'Toole and Walker might have found search performance to be efficient if they had used a disparity larger than 6 to 7 min of arc (Table 1).

Résumé

Nakayama et Silverman (1986) ont proposé que lors de la recherche d'une cible définie par une conjonction de couleur et de profondeur stéréoscopique, les observateurs divisent l'espace 3D selon des plans de profondeur séparés, et recherchent alors rapidement chaque plan tour à tour, réduisant de ce fait la recherche « conjonctive » (qui est coûteux en temps) à un certain nombre de recherches de « caractéristiques » (qui s'effectuent généralement rapidement) dans l'espace en couleur. Dans leur étude, ils ont utilisé deux plans de profondeur fortement séparés par stéréoscopie et ont observé, conformément à leur hypothèse, que la pente de la fonction reliant le temps de réponse au nombre d'items présents était faible. Ici, nous avons tenté de déterminer si la pente de recherche dépend de la magnitude de la séparation induite par stéréoscopie entre les plans où la recherche doit s'effectuer (c.-à-d., l'importance de la disparité binoculaire). La pente obtenue indique que i) une recherche rapide se produit seulement avec les disparités au-delà de 6 minutes d'arc, valeur excédant amplement le seuil stéréo, et que ii) l'inclinaison de cette pente augmente de façon importante dans le cas de disparités moins prononcées. L'applicabilité du mode de recherche proposé par Nakayama et Silverman se limite ainsi à de fortes disparités ; des stratégies de recherche moins efficaces sont nécessaires lorsque la disparité est plus faible, puisque dans de telles conditions, les items propres à un plan sont plus susceptibles d'interférer avec ceux des autres plans.

Mots-clés : recherche visuelle, recherche de conjonctions, profondeur stéréoscopique, couleur

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