Serial and parallel processing of visual feature conjunctions

Ken Nakayama & Gerald H. Silverman

Smith-Kettlewell Eye Research Foundation,
Pacific Presbyterian Medical Center, San Francisco,
California 94115, USA

Treisman and others[1–3] have reported that the visual search for a target distinguished along a single stimulus dimension (for example, colour or shape) is conducted in parallel, whereas the search for an item defined by the conjunction of two stimulus dimensions is conducted serially. For a single dimension the target 'pops out' and the search time is independent of the number of irrelevant items in the set. For conjunctions, the search time increases as the set becomes larger. Thus, it seems that the visual system is incapable of conducting a parallel search over two stimulus dimensions simultaneously. Here we extend this conclusion for the conjunction of motion and colour, showing that it requires a serial search. We also report two exceptions: if one of the dimensions in a conjunctive search is stereoscopic disparity, a second dimension of either colour or motion can be searched in parallel.

Visual search experiments were conducted with the aid of a Commodore 64 microcomputer and colour television monitor. Two types of experiment were performed, those where the observer's task was to see the unique target which differed from all others in one dimension only (simple); and those where the observer had to find the unique target which was defined by two dimensions (conjunction). The stimulus consisted of a variable size array containing either 15, 25 or 35 targets (see Fig. 1). Each of these targets was a random pattern containing 16 picture elements or pixels. Depending on the experiment (see Fig. 2), the targets were clearly distinguishable either in terms of colour (red versus blue), motion (up versus down) or stereoscopic depth (either in the fixation plane or in front). In the case of stimulus motion, each target formed a rectangular 'aperture' behind which a continuous array of random dots could be moved, either up or down.

The observer was aware of the particular dimension(s) to be searched before the beginning of each block of trials; the task was to press a button as soon as the target was seen. To eliminate false-positives, the array remained visible for an additional 800 ms after the response. This enabled the observer to scrutinize the display and to verify whether his identification was correct. The data associated with mistakes were discarded.

Each set of experiments had the same overall design and differed only in the choice of stimulus dimensions to be searched. In any given experiment, two stimulus dimensions were used: motion-and-colour (M-C); stereo-and-motion (SM), or stereo-and-colour (SC). For the simple search, the observer was required to find the target that was distinguished by a unique feature along a single dimension. In the case of motion (M) it was the target which moved in the opposite direction to all others, with colour being randomly assigned to all targets on an equiprobable basis (Fig. 2*a*). For the case of stereo (S), it was the single target which had a different binocular disparity from all other targets, with colour being randomly assigned to the targets on an equiprobable basis. For the case of colour (C), it was the single target which had the odd colour with the different directions of motion being randomly assigned.

Our first set of experiments extend and confirm previous work[1,2] showing that the search for a single feature is conducted in parallel. Reaction times are short and remain constant as the set size increases. Lower reaction time functions designated C, S and M (Fig. 3) refer to the simple search for colour, stereo and motion, respectively. All indicate that for the single-dimensional search, the processing is pre-attentive and effortless.

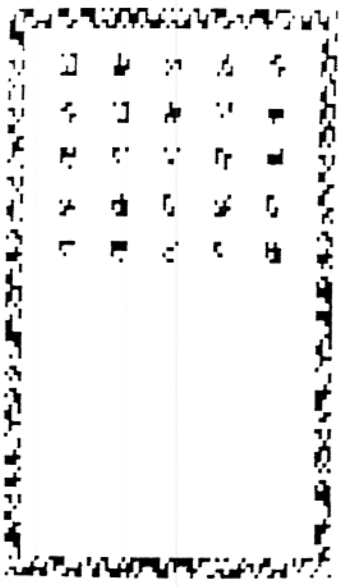

Fig. 1 The stimulus array contained either 35 targets (7 rows), 25 targets (5 rows) or 15 targets (3 rows) and was bordered with a frame to ensure stereoscopic fusion in the binocular experiments. For observer K.N., the stimuli had the following parameters: target size 0.4×0.5°, frame size 7.5×13°, vertical spacing of targets (1.0°), horizontal spacing of targets (1.2°), disparity 20 arc min, velocity $3.75^{\circ}\,\mathrm{s}^{-1}$. All stimulus parameters were 25% smaller for observer J.S.

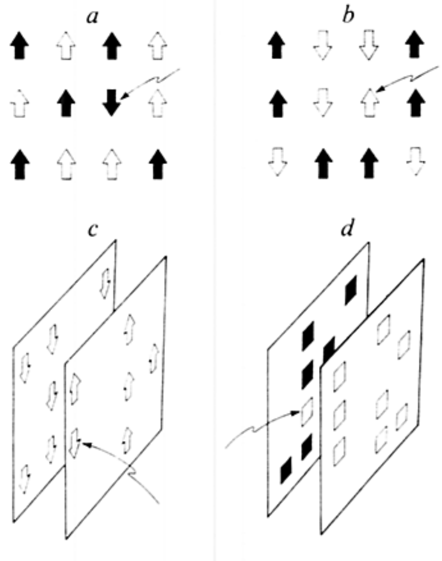

Fig. 2 *a*, Schematic description of the simple one-dimensional search for a discrepant motion. The observer must find the single target that has the anomalous motion with respect to all motions, targets are randomly coloured. *b*, Conjunctive search for colour and motion. Blue distractors move down, red distractors move up. The target breaks this pattern and is either a blue moving up or a red moving down. *c*, Conjunctive search for stereo and motion. All distracting targets in the front plane are moving up and those in the back plane are moving down. Relevant target either is in front and moves down or in back and moving up. *d*, Conjunctive search for stereo and colour. Distracting targets in the front plane are blue and those in the back plane are red. Relevant target is either red in front or blue in back. Open symbols, blue colours; filled symbols, red colours. Target to be found is marked by small pointer.

Conjunctive search, however, has been shown to require serial processing. We therefore expected that a search requiring the conjunction of motion and colour would also be conducted in serial. The irrelevant targets (distractors) for this experiment

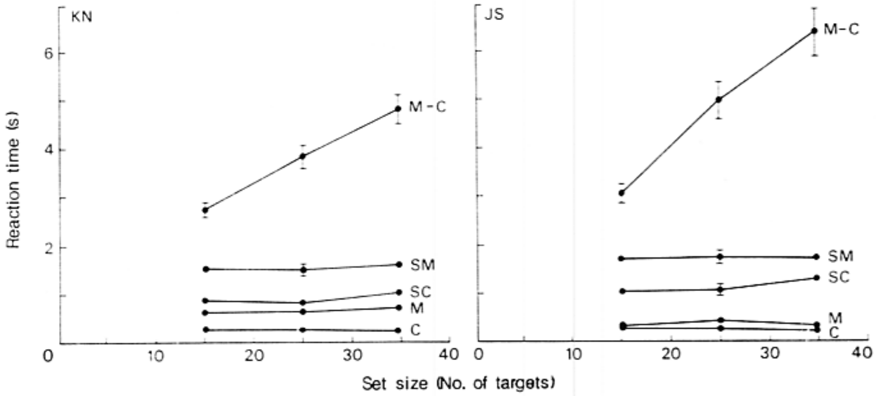

Fig. 3 Reaction times plotted as a function of the number of elements in the set to be searched. Results from two classes of experiments are shown. Conjunction: motion-colour (M-C), stereo-motion (SM), stereo-colour (SC). Simple: colour (C), motion (M), stereo (S). Note that for the conjunctive search of M-C, the anomalous target becomes more difficult to find as set size increases. This is not the case for the conjunction of SM or SC. All plotted reaction times represent the mean of at least 40 separate trials, preceded by at least 40 unscored practice trials.

were coloured either red or blue on a random equiprobable basis, with upwards motion linked to the red distractors and downwards motion linked to the blue. The relevant target broke this pattern, so it could be either a red moving down or a blue moving up (Fig. 2*b*). Compared with the simple search, observers found this task to be extremely difficult—they were unable to perform a parallel search for the anomalous motion over a given colour. Instead, they resorted to searching very small portions of the display, almost target by target. These subjective impressions were amply supported by the reaction time functions. The M-C function rose steeply (>100 ms per item) for increasing set sizes, confirming our expectation that the conjunctive search for motion-and-colour is indeed serial (Fig. 3).

In our final set of experiments we introduced the conjunction of stereoscopic disparity with either motion or colour. We generated two separate images on the television monitor and used crossed-polaroid filters to obtain the necessary dichoptic separation to produce the stereograms. The fixation plane was defined by a rectangular border which enclosed the targets and was always visible between trials. The individual targets were randomly assigned to either depth plane with equal probability. For the case of stereo-and-motion, the distractors in the front plane were always moving up and those of the back plane were always moving down. The target to be found was either moving down in the front plane or moving up in the back plane (Fig. 2*c*). For the case of stereo-and-colour, the distractors in the front plane were always blue and those in the back plane were always red. The target to be found was either a red in the front plane or a blue in the back plane (Fig. 2*d*).

In comparison with the case of motion-and-colour, these conjunctive tasks were qualitatively different and much easier. The observer had the distinct impression that each plane could be searched almost effortlessly, in turn. Correspondingly, the reaction time functions for each of these searches are constant over set size, never rising to the high values of reaction time which we found for the M-C search. This can be seen in the functions for SM and SC in Fig. 3. It seems that the visual system can perform a parallel search in one depth plane without interference from target-like distractors in another depth plane.

Our data suggest that the visual system can sequester processing or restrict attention in the spatial dimension (see refs 4, 5) but not to other visual dimensions such as colour and motion. Treisman[2] found that observers can attend to different two-dimensional loci in a complex visual scene, serially, yet perform a search within a given two-dimensional region, in parallel. We show that an analogous process occurs with different stereo-depth planes. Each depth plane can be processed in turn, allowing a parallel search within each plane.

We speculate that retinal disparity in addition to retinal locus has priority when compared with other visual stimulus dimensions; perhaps they constitute a set of primary indices to which the other visual attributes are linked[6]. As such, the results can be related to the anatomical organization of visual cortical projection areas, suggesting a segregation and duplication of visual features according to disparity. Thus, visual features of motion and colour at one disparity could be separately encoded and duplicated at other disparities. This notion of conjunctive parallel processing for dimensions linked to disparity finds a neurophysiological correlate in visual cortex area MT for the case of stereo motion[6] where single cells are selectively tuned to both direction and disparity. The existence of comparable cells selective for both colour and disparity has yet to be reported.

Conversely, the serial search associated with the conjunction of motion and colour seems to preclude the existence of single units selectively tuned to both motion and colour, consistent with recent evidence regarding the functional segregation of colour and motion information within cortical area V2 (refs 7-10) as well as their separate corresponding target destinations in V4 and MT. Cells in V4 are sensitive to wavelength differences but not to the direction of motion[11], whereas MT cells are sensitive to motion and not to wavelength[12].

This work was supported in part by grants 5P 30-EY01186 and EY05408 from NIH and (83-0320) from AFOSR.

Received 24 October 1985; accepted 13 January 1986.

1. Treisman, A. *Cogn. Psychol.* **12,** 97-136 (1980).
2. Treisman, A. *J. exp. Psychol.* **2,** 194-214 (1982).
3. Walters, D. B., Biederman, I. & Weisstein, N. *Invest. Ophthal. vis. Sci. Suppl.* 238 (1983).
4. Downing, C. & Pinker, S. in *Attention and Performance* Vol. 11 (eds Posner, M. I. & Marin, O. S. M.) 171-187 (Erlbaum, Hillsdale, New Jersey, 1985).
5. Hillyard, S. A. & Munte, T. F. *Percep. Psychophys.* **36,** 185-198 (1984).
6. Ballard, D. H. *Tech. Rep.* No. 133 (Univ. Rochester, 1984).
7. Maunsell, J. H. R. & van Essen, D. C. *J. Neurophysiol.* **49,** 1148-1167 (1983).
8. Shipp, S. & Zeki, S. *Nature* **315,** 322-325 (1985).
9. Hubel, D. H. & Livingstone, M. S. *Nature* **315,** 325-327 (1985).
10. DeYoe, E. A. & Van Essen, D. C. *Nature* **317,** 59-61 (1985).
11. Maunsell, J. H. R. & van Essen, D. C. *J. Neurophysiol.* **49,** 1127-1147 (1983).
12. Zeki, S. M. *Cold Spring Harb. Symp. quant. Biol.* **40,** 591-600 (1975).

Printed in Great Britain by Macmillan Production Ltd., Basingstoke, Hampshire

ERRATA

Nature erred by publishing an incomplete version of figure 3. The complete figure is reproduced below, including data from the stereo alone condition (S).