Cue Search and Comparison Processes in Visual Search for Letters*

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ABSTRACT

In two experiments, subjects searched four- and eight-letter arrays for the presence of a T or an F. The position of the target was indicated by a bar marker presented at one of seven stimulus onset asynchronies (SOA's); −100, −25, 50, 125, 200, 275, or 350 msec. In Experiment I, SOA conditions were blocked; in Experiment II, SOA conditions varied randomly from trial to trial. In both experiments array size and SOA interacted. With eight-letter arrays, reaction time increased linearly with SOA with a slope less than one. With four-letter arrays, reaction time increased with SOA but reached asymptote at the level of no-cue control reaction times at the 125 msec SOA. The results were interpreted as supporting the notion that cue search and comparison processes may function concurrently.

When people search through arrays for a particular target letter, their search times are typically shorter when the position of the target is cued than when position cues are withheld. Effective cues have been bar markers presented adjacent to the target (Holmgren, 1974; Jonides, 1976; Logan, 1977) or properties of the letters themselves other than their identity, e.g., orientation or colour, which distinguish the target from the non-targets (Logan, 1976a). Two explanations of the effect have been offered, both of which distinguish two processes, a *cue-search process* to deal with the cue, and a *comparison process* to deal with the target (Gardner, 1973; Holmgren, 1974). Both suggest that cueing will reduce search time whenever cue search coupled with comparison is faster than comparison by itself. Since cue search and comparison both must extend in time, it is reasonable to ask whether information relevant to comparison may be gained before cue search finishes. Indeed, the two explanations differ on this issue.

Holmgren (1974) would argue that it cannot. He suggests that cue search precedes comparison. It locates the cue and directs the comparison process to the appropriate position. Only then does the comparison process gain information from the array. Alternatively, Gardner (1973) has suggested that the cue search process simply increases the weight of information from the cued position as it converges on the comparison process. He would argue, then, that information relevant to comparison could be gained before cue search finished, but at a slower rate corresponding to the lower weight.

From Gardner's suggestion, it follows that the more information gained during cue search, the less remains to be gained after cue search finishes. Thus, the more time spent in cue search, the less time need be spent subsequently in comparison. Holmgren's suggestion has no such implications, so distinguishing predictions can be developed as follows: from Gardner's

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point of view, the reaction time interval RT may be divided into three parts, t_1, t_2, and k which represent, respectively, the time from stimulus onset until cue search finishes, the time spent subsequently in comparison, and a constant time for response selection and motor processes. Thus

$$RT = t_1 + t_2 + k. \quad (1)$$

The comparison process accumulates information until an amount β is obtained, and information may be accumulated at two rates, s_{nc}, the normal rate of accumulation when no cue is presented, and s_c, a faster rate possible only after the cue process finishes. (Both rates are expressed in units of β per unit time.) Thus, Gardner would argue that on trials on which a cue is presented

$$\beta = s_{nc}t_1 + s_c t_2. \quad (2)$$

The implications become clear if (2) is solved for t_2 and the result is substituted in (1) to yield

$$RT = t_1(1 - (s_{nc}/s_c)) + (\beta/s_c) + k. \quad (3)$$

Gardner's suggestion implies that s_{nc} in (2) and (3) is greater than zero (but less than s_c) since information may be gained during t_1 at rate s_{nc}. If this is so, RT is a linear function of t_1 with a slope less than one. Alternatively, Holmgren's suggestion implies that s_{nc} is zero in (2) and (3) since no information may be gained during t_1, so the slope of the function relating RT to t_1 should equal one. These predictions distinguish the alternatives.

Gardner's view also implies boundary conditions for the relation between RT and t_1. On some occasions, enough information may accumulate during t_1 (i.e., β units) for comparison to finish before cue search. This will occur whenever t_1 equals or exceeds β/s_{nc}, the time required to complete comparison without a cue. Thus RT will increase linearly with t_1 only when t_1 is less than β/s_{nc}. When t_1 equals or exceeds β/s_{nc}, RT will be constant at $(\beta/s_{nc}) + k$. Holmgren's view implies no such boundary conditions for the relation: Equation (3) should hold for all values of t_1 whenever the cue search process is engaged. However, Holmgren might argue that subjects who know the values of t_1 and β/s_{nc} relevant to the next trial may choose to engage the faster process, and so produce performance that follows the boundary conditions implied by Gardner's view. Because of this, performance that follows the boundary conditions cannot be interpreted as supporting Gardner's position uniquely, though it is certainly an interesting prediction.

We report two experiments in which we varied the stimulus onset asynchrony (SOA) between an array containing a target letter and a bar marker cue indicating the target's position (positive values of SOA indicate bar markers presented after the onset of the array). Assuming the time to process the bar marker once it has been presented is constant for all SOA's, SOA is an estimate of t_1, the time until the cue process finishes. The slope of the function relating reaction time to SOA is an estimate of the quantity $(1 - (s_{nc}/s_c))$, which should be less than one if Gardner is correct but equal to one if Holmgren is correct.

We also varied the number of non-target letters present in the array with the target, and we collected data in separate no-cue control conditions. Pilot work suggested that with the larger, eight-letter arrays, reaction time would increase with SOA over the range of SOA's we employed (−100 to 350 msec). Performance here should provide an estimate of the quantity $(1 - (s_{nc}/s_c))$ to distinguish the alternative explanations. With the smaller, four-letter arrays, however, reaction time was expected to reach the level of no-cue controls in the middle of the range of SOA's so that performance that follows the boundary conditions of (3) might be observed. We expected that the asymptotic cued reaction times would not exceed corresponding no-cue control reaction times since both are estimates of the quantity $(\beta/s_{nc}) + k$.

The two experiments were exact replications except that the different SOA's were blocked in Experiment I but varied randomly from trial to trial in Experiment II. In both experiments array size varied randomly from trial to trial and no-cue control conditions were run in separate blocks. The blocking of SOA conditions was varied to assess the extent to which the pattern of performance depended on subjects' knowledge of t_1 and β/s_{nc}.

METHOD

Subjects

A separate group of 16 summer-session students and laboratory staff from Queen's University served in each experiment. No subject reported any visual defect. In Experiment I, seven subjects were male and nine were female. In Experiment II, six subjects were male and ten were female.

Apparatus and Stimuli

The arrays and bar markers were presented on a cathode ray tube (Tektronix No. 604) supplied with P4 phosphor. Temporal and spatial parameters were controlled on-line by a DEC PDP-8/e computer. The program also measured reaction time from the onset of the array and recorded the accuracy of each response.

The arrays contained either four or eight different capital letters. Eight-letter arrays were presented in two rows of four letters, one above and one below the fixation point. Four-letter arrays were presented in one row of four letters. In half of the arrays, the row appeared above the fixation point, and in the other half, it appeared below. Each array contained one target letter, a T or an F. Each array size was represented by 128 different arrays in which each target letter appeared in each position equally often. Within sampling limitations, each non-target letter (all remaining letters except Q and I) appeared in each position equally often. The bar marker was a capital I which appeared above the target letter if it was in the top row, and below it if it was in the bottom row. The fixation point was a small dot in the centre of the array.

A head rest was used to maintain a constant viewing distance of 78 cm. At this distance, the eight array positions subtended approximately 1°50′ of visual angle horizontally and 55′ vertically. Each letter subtended about 22′ × 22′ of visual angle, and the vertical separation between a bar marker and a target letter was about 11′ of visual angle.

Stimulus onset asynchrony was varied from −100 to 350 msec in 75 msec steps. The arrays were exposed for 500 msec, and the bar markers for 100 msec. However, at the −100 msec SOA, the bar markers were exposed for 25 msec to equate phenomenal brightness. Five hundred msec before the array appeared, the teletype bell was rung as a warning signal. The interval between trials (i.e., from the onset of subject's response to the onset of the warning signal) was held constant at 4 sec. After each block of 32 trials, subjects were allowed a 30-sec rest period signalled by the termination of the fixation point. At the end of the interval, the teletype bell rang and the fixation point re-appeared. Four seconds later the warning signal for the first trial of the next block occurred.

During testing, the room was dimly lit, and the time required for instructions and practice served as a dark adaptation period. After the first block, experimenter left the room and returned 30 minutes later when the experiment terminated.

Procedure

Each subject completed 256 experimental trials in eight blocks of 32 trials. Within each block, each array size and target letter appeared equally often in a random sequence determined separately for each subject. In both experiments, the arrays were presented without a bar marker in one block. For the other seven blocks in Experiment I, only one SOA occurred in each block, while in Experiment II every SOA occurred at least once in each of the seven bar-marker blocks. Each experiment used eight orders of blocks, and two subjects received each order in each experiment. The orders were determined by a balanced Latin square.

In each experiment, eight subjects pressed one button with the index finger of their right hand to indicate that the array contained a T, and another button with the index finger of their left hand to indicate that the array contained an F. For the other eight subjects in each experiment, the correspondence between buttons and targets was reversed. Assignment to these conditions was orthogonal to the assignment to the orders of blocks.

Before the experimental trials began, each subject completed 32 practice trials with the target letters alone. During practice, each target letter appeared in each of the eight array positions twice.

RESULTS AND DISCUSSION

In each experiment, each subject completed 16 trials under each combination of array size and SOA conditions. Mean reaction times and standard deviations were

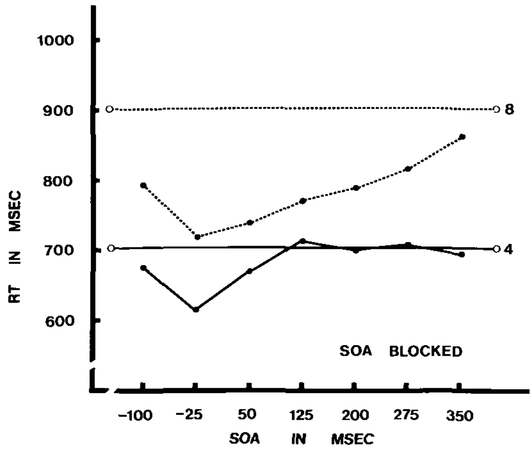

FIGURE 1 Mean reaction time in Experiment I as a function of SOA (array size and cueing conditions are parameters: solid lines = four-letter arrays; broken lines = eight-letter arrays; filled circles = cued conditions; open circles = no-cue controls; no-cue control points are connected by a horizontal line to facilitate comparison).

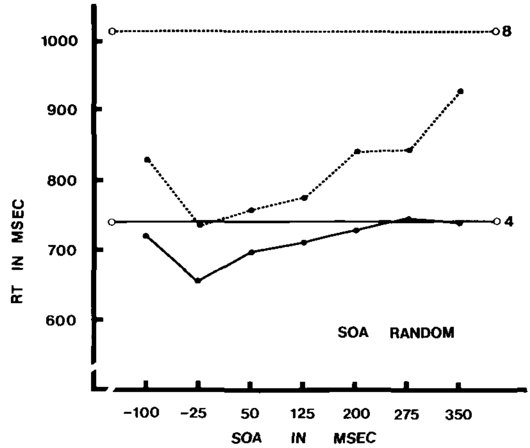

FIGURE 2 Mean reaction time in Experiment II as a function of SOA (array size and cueing conditions are parameters: solid lines = four-letter arrays; broken lines = eight-letter arrays; filled circles = cued conditions; open circles = no-cue controls; no-cue control points are connected by a horizontal line to facilitate comparison).

computed for correct responses for each subject. Mean reaction times across subjects are shown in Figures 1 and 2 for Experiments I and II, respectively. Mean standard deviations and error rates appear in Table 1. Altogether, three analyses of variance were performed on reaction times from each experiment. One included data from all conditions, one excluded data from the no-cue control conditions, and one excluded data from the −100 msec SOA conditions and the no-cue controls. In all

TABLE I
Mean within-subject standard deviations and proportions of errors as a function of array size and SOA in Experiments I and II

Experiment	Array size		Stimulus Onset Asynchrony −100	−25	50	125	200	275	350	No cue
SOA blocked (I)	4	*SD*	170	139	158	149	159	176	168	180
		errors	.05	.03	.05	.04	.03	.03	.03	.03
	8	*SD*	229	169	162	151	171	211	222	266
		errors	.11	.04	.04	.03	.06	.05	.04	.14
SOA random (II)	4	*SD*	193	148	134	167	147	180	182	185
		errors	.02	.05	.02	.03	.02	.02	.02	.05
	8	*SD*	228	183	161	168	189	179	238	303
		errors	.07	.03	.05	.06	.04	.05	.05	.04

TABLE II
Summary statistics from two-way analyses of variance on mean reaction times from all conditions of Experiments I and II (all p's < .01)

		F-ratios	
Effect	*df*	Experiment I	Experiment II
Array size	1, 15	141.26	217.43
SOA	7, 105	8.18	28.55
Array size × SOA	7, 105	7.31	17.30

analyses the main effects of array size and SOA and their interaction were significant beyond the .01 level. Summary statistics from the analyses including data from all conditions are presented in Table II.

The figures show similar interactions between array size and SOA in the two experiments, and two aspects of the interactions are relevant to the hypotheses under consideration. First, with eight-letter arrays, cued reaction times were consistently faster than the no-cue controls, and excluding the −100 msec SOA, reaction time increased regularly over the entire range of SOA's. These data represent points within the boundary conditions of equation (3). The slope of the best-fitting linear function relating reaction time to positive SOA is an estimate of the quantity $(1 - (s_{nc}/s_c))$, the slope of equation (3), which should be less than one if information relevant to comparison can be gained during cue search (Gardner's suggestion), but equal to one if it cannot (Holmgren's suggestion). Linear functions were fitted to each subject's data individually. The average functions were .408(SOA) + 716 for Experiment I and .548(SOA) + 720 for Experiment II. The slope values of both functions were significantly less than one, $t(15) = 7.590$, $p < .01$ for Experiment I, and $t(15) = 8.863$, $p < .01$ for Experiment II, but they did not differ from one another, $t(30) = 1.505$, $p < .20$. These findings confirm the prediction derived from Gardner's suggestion and disconfirm the prediction derived from Holmgren's: They show that information was gained before cue search finished so that less time was required for subsequent comparison the longer the SOA.

We wished to compare the slopes of the SOA functions with estimates from existing data. Since the slopes estimate the quantity $(1 - (s_{nc}/s_c))$, all we need from existing data are estimates of the rates of processing with and without a cue (s_c and s_{nc}, respectively). In most studies of visual search, reaction time increases linearly with array size, and the slope of the function (in msec/item) is usually used to test hypotheses about the rate of processing within the comparison stage (Atkinson, Holmgren, & Juola, 1969; Holmgren, 1974; Logan, 1976b, 1977; see also Sternberg, 1969). Specifically, the slope of the array size function, expressed as time per unit information, is the reciprocal of the rate of processing within the comparison stage, expressed as information per unit time (as are s_c and s_{nc}). Thus, the quantity $(1 - (s_{nc}/s_c))$ can be estimated from the quantity (1 − (slope cue/slope no cue)). Holmgren (1974) and Logan (1976a) have provided appropriate data: they varied array size (4 levels) and the presence or absence of a cue indicating the target's position (SOA = 0). Of 10 estimates computed from their data and displayed in Table III, nine fell within the 95 per cent confidence limits of the mean value, .478, obtained in the present experiments. Holmgren's and Logan's data thus agree with the present findings and independently confirm predictions derived from the notion that information relevant to comparison may be gained during cue search. It is interesting that Holmgren's data led him to the opposite conclusion.

The second relevant aspect of the interactions between array size and SOA seen in the figures is the relation between reaction time and SOA with four-letter arrays. Here cued reaction times were consistently faster than no-cue controls only for SOA's less than 125 msec. Reaction time increased regularly with SOA within this range (again

TABLE III
Estimates of the quantity $(1 - (s_{nc}/s_c))$ from existing data

Logan, 1976a			Holmgren, 1974		
Experiment	Cue type	$(1 - (s_{nc}/s_c))$	Experiment	Response	$(1 - (s_{nc}/s_c))$
I	Red	.399	I	Yes	.383
	45° tilt	.513		No	.501
II	15° tilt	.273*	II	Yes	.346
	30° tilt	.322		No	.558
III	15° tilt	.396			
	30° tilt	.310			

*Outside the 95% confidence limits of the value obtained in Experiments I and II (.478).

excluding the −100 msec SOA) but appeared to asymptote at the level of no-cue controls with longer SOA's. These data represent points that cross the boundary conditions of equation (3). For SOA's of 125 msec or more, the comparison process can finish before the cue process, and the asymptotic reaction times should equal no-cue control reaction times since both are estimates of the quantity $((\beta/s_{nc}) + k)$, the time to complete comparison and emit a response without a cue. In Experiment I the mean asymptotic cued reaction time (the mean of the 125-, 200-, 275-, and 350-msec SOA's) was 3 msec longer than the mean no-cue control reaction time, and in Experiment II the mean asymptotic cued reaction time was 7 msec shorter than the no-cue control. The close agreement between the two estimates in two experiments is encouraging. It is entirely consistent with the notion that information relevant to comparison may be gained during cue search; it suggests that concurrent comparison may finish before cue search.

Unlike the slope data, these findings do not disconfirm Holmgren's suggestion. In the Introduction we suggested that subjects who could not engage the cue process and the comparison process concurrently might produce asymptotic cued reaction times equal to no-cue controls if they knew in advance how much time would be required to process (compare) the array with and without the cue. Trial-to-trial variation of SOA conditions in Experiment II versus the blocked presentation in Experiment I, together with trial-to-trial variation of array size in both experiments, ought to have created enough uncertainty about the relative durations of the two processes to disrupt performance substantially, yet performance followed the boundary conditions equally well in both experiments. In particular, the transition of control from the cue process, coupled with comparison until the asymptote, to the comparison process, by itself after the asymptote, was remarkably smooth in both experiments.

We assessed the effect of blocking versus randomizing SOA conditions by including experiments as a between-subjects factor in two analyses of variance on the reaction time data. One analysis included data from all conditions; the other excluded the no-cue controls and the −100 msec SOA. In both analyses, no effects involving experiments were significant, neither main effects nor interactions. The largest F-ratio involving experiments was found for the interaction of array size, SOA, and experiments in the analysis of data from all conditions, $F(7, 20) = 1.524$, $p < .20$. Blocked versus randomized SOA conditions thus had no significant effects, but we would prefer a more sensitive, within-subject design to conclude they had no effects. The observed effects, however, were not consistent with Holmgren's view.

Two further aspects of the data warrant discussion. First, in both experiments, cued reaction time was consistently longer with the larger, eight-letter arrays at every SOA. We might interpret this as consistent with Gardner's view since it suggests that the use of the cue did not eliminate processing in the other array positions and this processing interfered with the detection of the target (Colegate, Hoffman, & Eriksen, 1973; Eriksen & Hoffman, 1972; Eriksen & Rohrbaugh, 1970; Logan, 1976a). However, the effect may indicate more lateral masking with eight-letter arrays where the close spacing of the two rows may provide a further source of inhibitory influence not present with single-row, four-letter arrays (Townsend, Taylor, & Brown, 1971; Wolford & Hollingsworth, 1974).

The data do exclude a third interpretation which suggests that subjects may fail to use the cue on a constant proportion of trials, using the comparison process without the cue process by default. At each SOA, mean reaction time would represent a mixture of fast, constant-latency responses and slower, no-cue responses whose latencies depend on array size, so mean cued reaction time would increase with array size (see Logan, 1976a). Note that this interpretation predicts a slope less than one for the function relating reaction time to SOA since the effects of ignoring the cue would be greater the shorter the SOA. However, this interpretation must also predict greater variability with a cue than without, since cued reaction time is a mixture of two distributions with different means, and greater variability the shorter the SOA, since the means of the two distributions are farther apart the shorter the SOA. The mean standard deviations presented in Table 1 disconfirm both of these predictions. Whenever a cue reduced reaction time below the level of no-cue controls, cued standard deviations were smaller than no-cue standard deviations, and excluding the −100 msec SOA, standard deviations tended to become *smaller* as SOA became shorter. The interpretation thus excluded strengthens our interpretation of the SOA slopes less than one as supporting Gardner's position.

A final point of interest is the finding in both experiments of longer reaction times with the −100 msec SOA than with the −25 msec SOA. Previous investigators have found monotonic increases in reaction time as SOA increased from −100 msec (Colegate et al., 1973; Eriksen & Hoffman, 1972; Jonides, 1976), so this result is anomalous. Since our bar marker at the −100 msec SOA was exposed for a shorter duration than bar markers at the other SOA's (25 msec versus 100 msec), and since every other bar marker appeared concurrent with the array, we suggest that it was more difficult to align the bar marker with an array position at the −100 msec SOA, and this led to the increase in reaction time (see also Hearty & Mewhort, 1975). Since this factor is independent of the major experimental variables, we have considered the anomaly unimportant and have disregarded the −100 msec SOA in our interpretation of the data.

GENERAL DISCUSSION

The results of both experiments were in complete accord with predictions derived from the suggestion that information relevant to comparison may be gained during cue search. The slope of the function relating reaction time to SOA was less than one, and the function was bounded by the time required to complete comparison and emit a response without a cue: Cued reaction time reached asymptote at the level of no-cue controls.

The notion of concurrent cue search and comparison is consistent with the suggestion that location and identity information are processed independently in the visual system (Logan, 1975a, b; Milner, 1974). Cue search may depend on location information and comparison on identity information, and concurrent functioning without interference may be possible because of the independence of the underlying processes.

Concurrent cue search and comparison is also consistent with Logan's (1976b, 1977) finding that the functioning of the comparison process in visual search is not affected by concurrent activity unrelated to comparison. He suggested that much of the processing in visual search, particularly processing in the comparison stage, is an automatic consequence of stimulus presentation. Task-relevant behaviour is a product of the interaction between sets to respond in a particular way to specific patterns of perceptual activity and the current pattern of perceptual activity that results from stimulation. From this point of view, the set in the cue search process might be the rule 'if cue, facilitate the position it indicates' and the set in the comparison process 'if T, press left; if F, press right.' The sets await stimulus presentation much like Newell's (1973) production systems wait for their conditions to be met in short-term memory. Once a stimulus appears, information about the conditions of the various sets accumulates automatically at a rate determined by the structure of the system, until enough conditions are satisfied for a response to occur. In the present example, a T, a T and a cue, an F, and an F and a cue are all sufficient conditions for a response to occur. Notice that the set determines *whether* a response will occur, but not *when*. Reaction time will depend on stimulus conditions like SOA and array size and on the rates at which information may be accumulated which are largely independent of the set adopted. From this point of view, attention to the stimulus itself is not necessary for a response to occur. Rather, it is attention to the set that ensures that an appropriate response will occur, 'released' as it were by the first appropriate stimulus.

RESUMÉ

En deux expériences, les sujets ont à dépister la présence d'un T ou d'un F dans des ensembles de quatre et de huit lettres. La position de la lettre cible est indiquée par un repère présenté à l'une de sept asynchronies du déclenchement du stimulus (−100, −25, 50, 125, 200, 275, ou 350 ms). Dans l'expérience I, les conditions d'asynchronie sont massées; dans l'expérience II, ces conditions varient au hasard d'un essai à l'autre. Les résultats montrent une interaction entre les conditions d'asynchronie et la longueur de la série de lettres dans les deux expériences. Pour les séries de huit, le temps de réaction augmente de façon linéaire avec les conditions d'asynchronie, la pente étant inférieure à un. Pour les séries de quatre lettres, le temps de réaction augmente avec les conditions d'asynchronie, mais atteint son asymptote à 125 ms (comme pour les temps de réaction sans point de repère). L'interprétation voit dans ces résultats une confirmation de l'idée que les processus de recherche d'un repère et les processus de comparaison peuvent fonctionner de façon concurrente.

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