Vision Res Vol. 17, pp. 141 to 146. Pergamon Press 1977. Printed in Great Britain.

THE ROLE OF SMALL SACCADES IN COUNTING

EILEEN KOWLER and ROBERT M. STEINMAN
Department of Psychology, University of Maryland, College Park, MD 20742, U.S.A.

(*Received* 8 *March* 1976)

Abstract—Eye movements were recorded by a contact lens optical lever while subjects counted a repetitive pattern of closely spaced bars (7′–14′ apart) in a 2° field by either making saccades or maintaining the line of sight without saccades. Counting accuracy was slightly greater without saccades than with saccades even when saccade size approximated the separation of the bars. Saccades did improve counting accuracy when displays contained haphazardly-arranged odd shapes that easily formed distinct perceptual groups.

Next, we considered possible reasons why saccades improved counting accuracy with such displays and found that saccades were not needed to solve problems requiring visual imagery as has been proposed. Also, that a single saccade did not necessarily accompany each attention shift during counting. These results do not support proposals that counting accuracy is limited by oculomotor skill. Rather, they suggest that counting accuracy is limited by perceptual confusion in the display.

Saccades are essential to human visual information processing because the human retina is heterogeneous. This not only makes saccades essential but it also suggests that their characteristics could influence decisions human beings make about their visual world. This notion is not new. For example, Landolt (1891) reported that a row of dots or stripes could not be counted if their separation was less than 5′. Landolt used this psychophysical result to make an inference about oculomotor capacity. He proposed that the smallest voluntary saccade (*le plus petit angle que l'oeil puisse parcourir*) must be about 5′ because he believed that the ability to shift the line of sight in discrete steps limited the ability to count. Landolt's inference about saccadic capacity has recently been shown to be correct by accurate measurements of oculomotor performance—the smallest average voluntary saccade is about 5.7′ (Haddad and Steinman, 1973). But we still do not know if saccadic capacity determines counting accuracy. Specifically, must saccades be used to count and does their size determine the accuracy with which we can count? Our experiments answer these questions. They report details of the eye movement pattern while subjects counted repetitive and non-repetitive displays.

METHOD

Movements of the right eye were recorded with a contact lens optical lever whose output was used to make analog records of eye position. The noise level of the recording instrument (Haddad and Steinman, 1973) was 15″ with the 4° × 4° recording field used in the present experiments. The left eye was closed and covered and the head was supported by an acrylic dental biteboard.

Two subjects (the authors) were tested. One, Steinman, was an experienced eye movement subject. The other, Kowler, was running in her first eye movement experiment. Her only prior experience consisted of approx 1 hr on the biteboard during which she was aligned and calibrated.

EXPERIMENT 1: REPETITIVE PATTERNS

We counted repetitive patterns while our eye movements were recorded. Specifically, the bright bars of a vertical 85% contrast squarewave grating. The grating was generated on an display oscilloscope (Tk 604; P4 phosphor) in the conventional manner, i.e. by modulating the intensity of a homogeneous raster. The display was located 1.3 m in front of the right eye and the edges of the oscilloscope face were masked so that the visible portion subtended 2.3° horizontally and 1.2° vertically. The number of bright bars visible on any given trial ranged between 10 and 19. So, separations between corresponding points on the bright bars ranged from 14.2′ for the 10 bar display to 7.4′ for the 19 bar display. These bar patterns were used because the smallest separation was large enough to allow voluntary saccades to be used to step from one bar to the next. The size of the visible display was small enough so that even the outermost bars were clearly distinguishable when the center of the display was fixated.

The bar displays were presented for 7.6 sec. Before each presentation we fixated a 6.5′ dia black dot located at the center of a circular homogeneous field (3.8° dia). This field was produced by a "green" electroluminescent panel (Sylvania Panelescent lamp, Type 120). A beam splitter superimposed the centers of the pretest and test fields, only one of which was visible at a given time. The electroluminescent panel, seen before each test, was extinguished when the bar pattern appeared and counting began. At the end of the test the bar pattern was removed and the electroluminescent panel reappeared. The electroluminescent panel delayed the appearance of afterimages of the bars so the subject could report his count based only on visual information present during the test interval. When the luminance of the electroluminescent panel (0.34 cd/m^2) was set above the luminance of the bright bars (0.24 cd/m^2), counts were reported before afterimages appeared.

The subject started a counting test when no afterimages were visible and when he felt prepared to confront the bar pattern. One second after he started the test a randomly selected bar pattern appeared. The bars were visible for 7.6 sec. When the bars disappeared, the subject immediately reported his count. He was then given feedback as to the number of bars that were actually presented.

The test interval, like bar separation, was selected to allow the subject to use voluntary saccades to count. We used as a guide typical saccade rates during reading (3/sec) which means that as many as 23 saccades could be made during 7.6 sec. This seemed sufficient time because the largest number of bars presented was only 19.

We counted the number of bright bars while controlling our eye in two quite different ways. Under one instruction

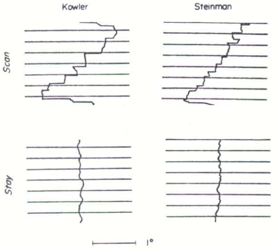

Fig. 1. Four representative records of horizontal eye movements of Kowler and Steinman counting a repetitive bar pattern under instructions to *Scan* and to *Stay*. Records are read from bottom to top. Horizontal lines are 1-sec time-markers. The bar below the records represents a 1° arc rotation.

(*Scan*) we used any saccadic eye movement pattern that we thought would allow us to count as accurately as possible. Under the second instruction (*Stay*) we were required to refrain from making any saccades whatsoever and count by shifting the mind's eye rather than by moving the eyeball around in the orbit. These instructions alternated between blocks of counting tests.

Results

Counting did not require saccades. This is illustrated in Fig. 1, where representative eye movement records under each instruction are reproduced. We made very few saccades on the average when we counted under instructions to *Stay* in place (Steinman's mean number of saccades/7.6 sec = 0.4, S.D. = 1.0, $N = 129$; Kowler's mean number of saccades/7.6 sec = 0.4, S.D. = 0.8, $N = 60$). We made many more saccades when we scanned and the number of our saccades differed markedly. Kowler's mean number of saccades during 7.6 sec counting tests under the *Scan* instruction was 5.6 (S.D. = 2.3, $N = 61$) and Steinman's was 12.7 (S.D. = 3.5, $N = 130$). The sizes of our saccades also differed (Steinman's mean horizontal saccades magnitude = 10.2′, S.D. = 6.8, $N = 216$; Kowler's = 24.6′, S.D. = 10.3, $N = 102$). Steinman not only tended to make more frequent, smaller, and less variable saccades he also tended to match saccade size to the separation of the bars. Kowler did not. This is illustrated in Fig. 2.

So, if Landolt were correct about the relationship between saccades and counting accuracy, what would we expect? First, and most important, counting accuracy should be better when saccades are made (*Scan*) than when they are not (*Stay*). Second, Steinman should count more accurately than Kowler when he makes saccades because he makes saccades more frequently, his saccades are smaller, and they tend to match the separation of the bars. Neither of these expectations was fulfilled as can be seen in Table 1 where counting accuracy is summarized.

The only support for Landolt is the fact that Steinman, who makes saccades more frequently and accurately, counted slightly more accurately than Kowler when he scanned, but this difference was not statistically reliable. Counting accuracy clearly did not depend on oculomotor skill because both subjects were most successful when they made almost no saccades at all.

EXPERIMENT 2: NON-REPETITIVE PATTERNS

Landolt believed (as might the reader who attempts to count the black bars in Fig. 3) that counting small repetitive patterns is accomplished by making small saccades. Count the bars. We believe you will keep losing your place. (Do not cheat by using a pencil or fingernail.) We experienced just this kind of difficulty. We kept losing track of precisely which bar

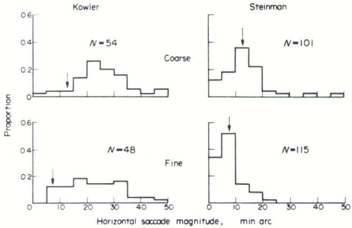

Fig. 2. Proportions of horizontal saccade magnitudes of Kowler and Steinman counting a repetitive display of bars under instructions to *Scan*. These histograms are based on a random sample of nine trials with the three coarsest (10–12) and nine trials with the three finest (17–19) bar displays. Arrows correspond to the average separations of the bars. The number of saccades (N) measured for each subject with the coarse and fine bars is also shown.

Table 1. Per cent correct counts (%c) and mean error on incorrect trials (Error) of subjects Kowler and Steinman when confronted with bar patterns under instructions to use saccades (*Scan*) or to suppress them (*Stay*)

	Kowler			Steinman		
	%c	error	*N*	%c	error	*N*
Scan	41	1.3 (0.6)	61	46	1.4 (0.5)	130
Stay	43	1.4 (0.7)	60	54	1.2 (0.4)	129

The chance expectation was 10% and the lowest possible error was 1.0. Standard deviations of the mean errors are given in parentheses and the number (*N*) of counting tests is also shown.

had just been counted when we counted with nothing but our line of sight.

The difficulty we experienced while counting repetitive patterns seemed to us to arise from difficulty in directing the mind's eye rather than difficulty in making saccades that were small enough. We thought that we knew how to go where we wanted but were uncertain about where we had been. Such considerations suggested that it might be useful to turn our attention to the perceptual nature of the display and we repeated the experiment with displays containing distinctive elements—elements that would allow us to keep track of where we had been as we moved the line of sight around the display. One such display is reproduced in Fig. 4.

Each display (*DEBRIS*) contained 7 to 16 items. The display, illuminated by a fluorescent lamp, was hidden from view between tests by a shutter. One second after the subject started a test, the shutter opened exposing a randomly selected display for 7.6 sec. The intertrial field and other procedures were the same as in the first experiment. All the items in each *DEBRIS* display were haphazardly arranged within a 2.3° dia circular field.

Results

Saccades helped when non-repetitive patterns were counted. This result is summarized in Table 2 where it can be seen that when we used saccades to count (*Scan*), our accuracy was about 50% higher than we stayed in place. Also, those errors that did occur rarely exceeded one item.

The details of the oculomotor performance underlying the contribution of saccades to counting accuracy are summarized in Table 3 and illustrated in Fig. 5. Two-dimensional eye movement records are reproduced in Fig. 6.

Steinman continued to make saccades somewhat more often than Kowler but the difference was not as large as was observed when the repetitive bar pattern was counted. However, differences between the

Fig. 3. This bar display, when held at normal reading distance (40 cm), will subtend 2.3° horizontally and 1.2° vertically.

Fig. 4. The diameter of this *DEBRIS* display, when held at a normal reading distance (40 cm), will subtend 2.3°.

subjects in saccade sizes and variability observed before are no longer apparent. Both of us made relatively large saccades (> 1/3°) and now Kowler shows a tendency to make smaller saccades when the items in the display become more numerous.

Do these results support Landolt's expectation? They do with respect to the importance of saccades in counting but they do not with respect to the relationship of saccade frequency or size to the accuracy of the count. This can be illustrated first by considering the correlation between the number of saccades and the number of *DEBRIS*. Kowler's Pearson rho was 0.32 ($N = 124$, $P \leq 0.01$) and Steinman's Pearson rho was 0.13 ($N = 99$, $P > 0.05$). Only Kowler's correlation was significant but it accounts for less than 10% of the variance. Similarly, the correlations between saccade size and number of *DEBRIS* do not support Landolt's expectation. They were not significantly different from zero for both subjects (Steinman's rho = 0.04, $N = 198$; Kowler's rho = −0.09, $N = 146$). These correlations show that we did not use our saccades to look from one item to the next.

Table 2. Per cent correct counts (%c) and mean error on incorrect trials (Error) of subjects Kowler and Steinman when confronted with *DEBRIS* under instructions to use saccades (*Scan*) or to suppress them (*Stay*)

	Kowler			Steinman		
	%c	error	*N*	%c	error	*N*
Scan	93	1.0 (0.0)	124	93	1.1 (0.4)	99
Stay	62	1.4 (0.7)	125	64	1.3 (0.5)	100

The chance expectation was 10% and the lowest possible error was 1.0. Standard deviations of the mean errors are given in parentheses and the number (*N*) of counting tests is also shown.

Table 3. The number of saccades/7.6 sec counting test (No. S) and saccade vector magnitude (SVM) in min arc of subjects Kowler and Steinman when confronted with *DEBRIS* under instructions to use saccades (*Scan*) or to suppress them (*Stay*)

	Kowler				Steinman			
	No. S	N_T	SVM	Ns	No. S	N_T	SVM	Ns
Scan	9.5 (4.1)	124	23.0 (10.1)	146	13.4 (5.7)	99	26.4 (12.5)	198
Stay	1.1 (1.5)	125	*		1.0 (2.1)	100	*	

Standard deviations are given in parentheses and the number of trials (N_T) and number of saccades (*N*s) are also shown. The SVM is based on exhaustive measurements of saccades in a random sample of 18 trials with the three coursest (7–9 items) and three finest (14–16 items) displays.

* The sizes of the small number of saccades occurring under the stay instruction were not measured.

EXPERIMENT 3: VISUAL IMAGES

Why do saccades help when non-repetitive patterns are counted if saccades do not move the line of sight from item to item? Perhaps the answer lies in the relationship between saccades and visual imagery proposed by Hebb (1968), Beritashvili (1969), and Lorens and Darrow (1962). These authors proposed that visual images require saccades. If true, this relationship might explain how saccades help when non-repetitive patterns are counted. Non-repetitive patterns would produce visual images that contain distinctive items which could be stored and used to keep track of where the line of sight has been as it moves about within each display. We would then expect counting to be better when saccades are made if saccades are the mechanism by which visual images are produced, providing these images are discriminally different.

We examined the importance of saccades to visual imagery by attempting to maintain a steady line of sight, without saccades, at the center of a grey disc (15′ dia) on a circular white background (3° dia) for 10 sec while we solved problems requiring visual imagery. For example, "How many windows are there on the second floor of your parents' home?" Such questions cannot normally be answered correctly without using the mind's eye to look around within some part of the *imagined* visual world. Neither of us knew the specific questions we would be required to answer until the 10-sec test began and we gave solutions as soon as the end of the test was signalled. On alternate trials (control) no questions were asked and we were required only to maintain the line of sight, without saccades, at the center of the grey disc. We used 10-sec trials because the question was asked during the first 2.5 sec of each trial, allowing about 7.5 sec for imagery.

Results

Visual imagery did not require saccades. Both of us answered all questions correctly despite the fact that we made saccades rarely (Steinman's mean number of saccades/10 sec test = 0.6, S.D. = 1.0, $N = 24$; Kowler's = 0.6, S.D. = 0.6, $N = 25$). The occurrence of saccades during visual imagery was not appreciably different than during control trials when our minds were occupied with a much less demanding task (Steinman's mean number of saccades/10 sec test = 0.3, S.D. = 0.6, $N = 24$; Kowler's = 1.0, S.D. = 1.0, $N = 25$).

Our results are consistent with prior reports that large eye movements ($>1°$) need not occur during successful visual imagery (Hale & Simpson, 1970; Janssen and Nodine, 1974). But, our result does show that *no* saccades need be made. Prior authors found none but were forced by limitations in their eye moni-

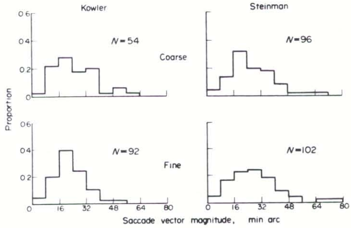

Fig. 5. Proportions of saccade vector magnitudes of Kowler and Steinman counting *DEBRIS* under instructions to *Scan*. These histograms are based on a random sample of nine trials with the three coarsest (7–9) and three finest (14–16) *DEBRIS* displays. The total number of saccades (*N*) measured for each subject with the coarse and fine *DEBRIS* is also shown.

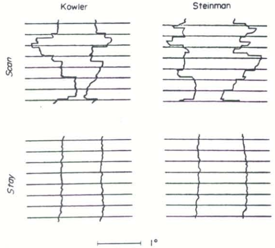

Fig. 6. Four two-dimensional records of eye movements of Kowler and Steinman counting *DEBRIS* under instructions to *Scan* and to *Stay*. Horizontal eye movements are shown in the trace on the left of each record. Records are read from bottom to top. Horizontal lines are 1-sec time-makers. The bar below the records represents a 1° arc rotation.

toring techniques to speculate that small saccades might have been made.

EXPERIMENT 4: ATTENTION

Since visual imagery could not help explain how saccades improve accuracy when *DEBRIS* is counted, we turned once again to our subjective impressions. Both of us had noticed that items in such displays form relatively stable groups of 2, 3 or 4. We both agreed that we counted *DEBRIS* by looking at one of these perceptually distinct groups and noticing how many items it contained. We then shifted attention to a neighboring group by making a saccade, noted how many items it contained and added that number to our running sum of the items in the display. (Count the items in Fig. 4 and see if you agree.)

We both believed that we switched attention between perceptually distinct groups by making a single saccade. Such saccades could be useful because they would permit us to shift attention rapidly and accurately before the items formed new perceptual groups. But, were our subjective impressions correct? Were we really using each saccade to shift attention to a new perceptual group?

We tested this notion by using saccades (*Scan*) to count *DEBRIS* while indicating when we shifted attention to a new perceptual group in the display. We indicated attention shifts by pressing a button that activated an additional channel on the 2-dimensional eye movement records. In all other respects the conditions were the same as those in Experiment 2.

Results

A single saccade did not necessarily accompany each shift of attention. Kowler made, on the average, one saccade each time she shifted attention (mean number of saccades/attention shift/7.6 sec test = 1.0, S.D. = 0.3, $N = 50$) but Steinman made more than twice as many saccades as attention shifts (mean number of saccades/attention shift/7.6 sec test = 2.3, S.D. = 0.7, $N = 100$). But despite our different use of saccades, our counting accuracy was virtually the same; Kowler had 92% correct, Steinman had 91% correct.

These results show that successful counting does not depend on a specific pattern of saccades in which each attention shift is accompanied by a single motor act. This result is consistent with our previous experiments. It shows that counting accuracy cannot be predicted from individual oculomotor characteristics.

Two additional implications of this experiment are: first, that it is dangerous to use the occurrence of saccades to interpret the sequence of mental events underlying serial processing of visual information (e.g. Noton and Stark, 1971) because saccades can reflect idiosyncratic motor habits rather than shifts in attention within a visual display. Second, oculomotor acts in visual information processing tasks are not readily accessible to conscious awareness. Even a highly experienced eye movement subject will, when engaged in visual information processing, be unaware of details of his eye movement pattern and confuse attention shifts with saccades. This is not a general characteristic of oculomotor acts, however, because the same subject, not occupied with a cognitive task, has no difficulty distinguishing attention shifts from even the smallest saccades (Haddad and Steinman, 1973; Steinman *et al.*, 1973).

DISCUSSION

Our findings do not confirm Landolt's (1891) suggestion that counting accuracy is limited by the ability to make small voluntary saccades. The disagreement may stem from differences in our experimental procedures. First, Landolt did not measure eye movements and second he did not ask his subjects to count. Instead Landolt determined the distance at which subjects reported that they could no longer count. He always used the same pattern (12 items) and only varied distance. This technique uses the subjective difficulty experienced by the subjects, rather than objective indications of performance, to serve as the basis of the inferred relationship between saccades and counting accuracy.

Our results also conflict with reports of modern authors. For example, Yarbus (1967, pp. 16–17) asserts that counting repetitive patterns is impaired when voluntary saccades are not made. We found that this is not the case but cannot explain the difference between Yarbus' and our result because Yarbus only makes reference to Landolt's data. More recently, other Russian workers, Gippenreiter, Romanov and Smirnov (1969) did measure eye movements and counting accuracy which they report qualitatively. They found that when bar separation was 20′–35′, the number of saccades equalled the number of bars and counting was performed with "accuracy and ease". However, when bar separation was 7′–10′ (the separation we also used), the number of saccades was lesss than the number of bars and counting "presented great difficulty". Gippenreiter *et al.* (1969) ascribe the reduction in counting accuracy to the existence of a saccadic "dead zone" which prevents the occurrence of saccades that are small enough to count fine repetitive patterns. They go on to propose a model for counting in which items in the display cannot be counted without inflow signals generated by saccades. They suggest that saccades are made from item to item. Each saccade generates an inflow signal that is monitored and stored as a number. The reported count is equal to the "number of the natural series" assigned to the last inflow signal.

Our results do not support this model.[1] We found that counting accuracy for repetitive patterns was highest when saccades were *not* made. Our results with non-repetitive patterns also are not supportive. We found that saccades improved counting accuracy when the elements to be counted formed perceptually distinct groups. With such displays counts were accurate (93%) but the number of saccades did not equal the number of items as would be predicted by Gippenreiter *et al.* (1969). We cannot reject the model completely, however, because it allows considerable latitude. Any motor act will do, e.g. a button press. We cannot be sure that we made no other motor responses that could have produced the required series of inflow signals because we only recorded eye movements.

What is the role of saccades in counting? We do not believe that their size limits the ability to count repetitive patterns because we found that counting accuracy, although low, was better when saccades were not made than when they were, even when saccades were as small as the separations between the items to be counted. This result suggests that perceptual confusion rather than motor skill constrains the count when displays are repetitive. But, we did find that saccades are valuable when perceptual confusion is removed by providing displays that form natural perceptual groups. This result suggests that saccades may provide the basis for counting accuracy and define its limit when perceptual confusion is prevented. Our experiments, however, are only suggestive because the saccades we made were large when we counted perceptually organized displays—3–5 times larger than our smallest voluntary saccade. It now becomes of interest to count displays where perceptually distinct groups are separated by distances as small as the smallest voluntary saccade. Under such conditions we may find that saccade size does limit counting accuracy. But, it seems equally plausible to us that counting very small perceptually organized displays may be as successful without any saccades because when all of the perceived groups fall near the center of attention, it may prove as easy to count with small shifts of the mind's eye as with small saccades.

[1]Our data also do not support motor models in which outflow signals, rather than inflow signals, are used to provide the basis for counting. We do not believe that such outflow signals are used in counting because we found that saccades do not improve counting of repetitive patterns. See MacKay (1966) for a general criticism of the role of motor outflow in perceptual and cognitive tasks. Our data offer some empirical support for MacKay's insightful suggestions.

Acknowledgements—We thank G. Haddad, J. Holmgren, W. Larkin, J. Levinson, P. McGrath, B. Murphy, J. Nachmias and B. Winterson for valuable suggestions and comments and G. Benson, M. Kowler, I. Nicholson and Y. Roder for technical assistance.

This research was supported by Grant 00325 from the National Eye Institute. A portion of the results was reported at the Psychonomic Society meeting in Denver, Colorado, November, 1975.

The computer time for this project was supported through the facilities of the Computer Science Center of the University of Maryland.

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