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Research Note

Human express saccades: extremely short reaction times of goal directed eye movements

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Summary. Human subjects were asked to execute a saccade from a central fixation point to a peripheral target at the time of its onset. When the fixation point is turned off some time (≈ 200 ms) before target onset, such that there is a gap where subjects see nothing, the distribution of their saccadic reaction times is bimodal with one narrow peak around 100 ms (express saccades) and another peak around 150 ms (regular saccades) measured from the onset of the target. Express saccades have been described earlier for the monkey.

Key words: Eye movements – Reaction time – Fixation – Attention – Express saccade

Introduction

We have recently reported the existence of goal directed saccadic eye movements in the monkey after extremely short reactions in the order of 75 ± 3 ms (Express saccades, E-saccades) (Fischer and Boch 1983). They occur in a situation where the central fixation point is turned off some time (80 to 300 ms) before the peripheral target appeared. According to Saslow (1967) human subjects produce also rather short reaction times (in the order of 150 ms) under these conditions (gap) as compared to the case where the fixation point remains on (overlap). However, there was no report to our knowledge of the existence of saccades after even shorter reaction times, that would correspond to the express saccades in the monkey. The indication of express saccades is not the magnitude of their reaction times but rather the existence of at least two clearly distinct peaks in the distribution (Fischer and Boch 1983). We have used the gap paradigm for human subjects and looked at the distribution of their saccadic reaction times (SRT) in order to find out whether or not humans would also be able to execute express saccades.

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Methods

Observers were 10 adults (20 to 40 years old) and 2 boys (9 to 16 years old). Three of them were members of our research group, the others were naive with respect to the experiment and were paid for their participation. Subjects were placed 65 cm in front of a translucent screen with their heads stabilized by means of a chin rest. Horizontal eye movements were monitored from one eye using a single infrared light emitting diode and two photocells coupled dc to a differential amplifier, a method basically described by Gauthier and Volle (1975) and modified by us in terms of the opto-electronic elements and the electronic circuitry of the amplifiers. Resolution was 0.2° for saccades with a dc-stability of about 0.5°. Saccadic reaction times were automatically determined by an electronic threshold detector and were directly displayed by a millisecond counter (Fischer and Boch 1983). Numbers were also fed to a minicomputer to built up the distributions and to calculate mean values and standard deviations of the reaction times. For the distributions we used a bin width of 10 ms if not stated otherwise. Eye movements were inspected trial by trial on a storage oscilloscope (triggered at the time of fixation point offset) and the detection of the saccade was indicated by interrupting the beam for 12 ms.

Subjects had to fixate a central (red) fixation point 0.25° in size on a dim homogeneous background of 0.1 cd/m^2. The fixation point remained visible either for a fixed period of 2 s or for a random time between 1 s and 3.5 s. The peripheral target consisted of another red spot 0.25° in size and appeared either always in the same position (4° to the right or 4° to the left of the fixation point) or its position was randomly changed between 4° to the right and 4° to the left. The temporal gap between fixation point offset and target onset was kept constant at 200 ms. For control measurements, however, we used different or even randomized gap durations. The target remained on for 2 s and after another 3 s the next trial began. The subjects' task was to maintain fixation at the central spot and to execute a saccade to the peripheral target when it occurred. Of course, every once in a while the subject would initiate a saccade upon the offset of the fixation point in particular when the time of its offset was kept constant. We, therefore, run a control experiment, where the subject had to initiate saccades on

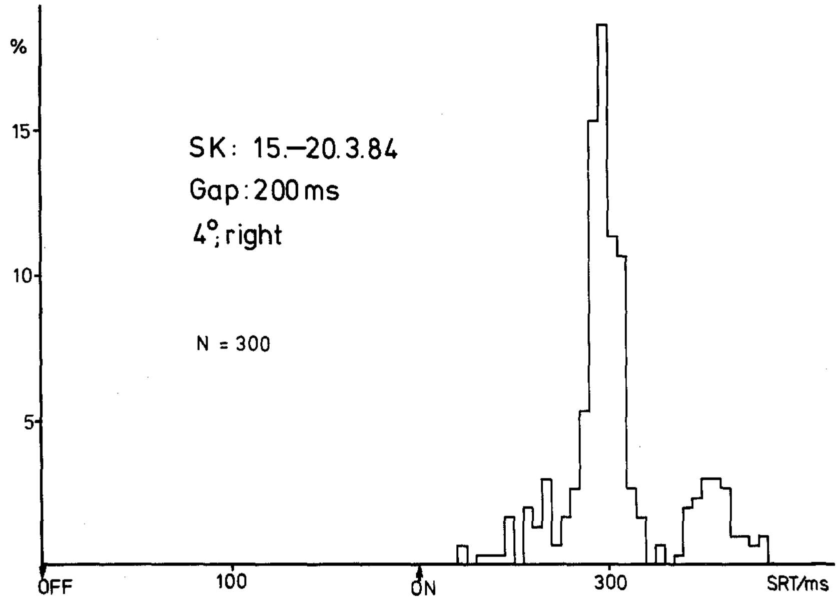

Fig. 1. Distributions of saccadic reaction times (SRT) of a single subject. Bin width: 5 ms. Zero at the abscissa corresponds to the time of fixation point offset; the target occurred 200 ms later marked by the arrow. The target occurred always in the same position (4° to the right) at always the same time. The large peak in the middle represents the population of express saccades, the smaller peak to the right represents the regular saccades

the command of fixation point offset in the absence of a peripheral target.

Subjects were immediately notified of the reaction time they produced trial by trial in all experiments with the exception of control runs (see Results). Single sessions consisted of 100–200 trials. In cases where one parameter was randomized between only 2 values (e.g. right – left) at least 100 saccades for each parameter were collected. No more than 4 sessions a day were required from a given subject. Altogether, the results reported below rest on the observation of about 30.000 saccades.

Results

1. The phenomenon

The basic result is illustrated by the distribution of the saccadic reaction times of a single subject in Fig. 1. The percentage of saccades falling into each bin (5 ms) is plotted versus the reaction time. At zero time the fixation point went off and the target appeared 200 ms later in always the same position. The distribution shows essentially three peaks. An early peak before 60 ms (from target onset), a large second peak around 100 ms and a smaller peak around 150 ms.

To identify the three peaks we did two experiments:

(i) The subjects were asked to make saccades of approximately the same size and direction upon the offset of the central fixation point when there was no target. The corresponding distributions of reaction times were unimodal with a peak around 50 ms. They show that many but perhaps not all of the early saccades in Fig. 1 must be attributed to trials where the subject unvoluntarily initiated eye movements upon the offset of the fixation point rather than upon the onset of the target. This notion is supported by our observation, that the early saccades in Fig. 1 with reaction times below 75 ms were almost all wrong in amplitude by more than 20%, whereas most of the later saccades giving rise to the two other peaks were correct.

(ii) Since subjects had the possibility to anticipate the location of the target, we randomized its position between 4° to the right and 4° to the left. The result is shown in Fig. 2A and B. First of all, the early reaction times seen in Fig. 1 are missing. Both distributions are clearly bimodal with one peak around 115 ms and a second peak around 150 ms. These two peaks are easily identified by the large peak around 100 ms and the smaller peak around 150 ms of Fig. 1.

The bimodality of the distributions and the visual condition under which they are obtained led us to identify the peak around 100 ms with the express saccades described for the monkey and the 150 ms peak with the regular saccades known from monkey as well as from humans. The fact, that the express saccades of monkeys have reaction times around 75 ms whereas those of humans have values around 100 ms will be considered in the Discussion.

To further identify the regular saccades as such we run tests, where the fixation point went off as the target came on (gap reduced to zero). Under these conditions the distributions became unimodal with peaks around 180 ms. This increase of the mean reaction times of the regular saccades replicates the

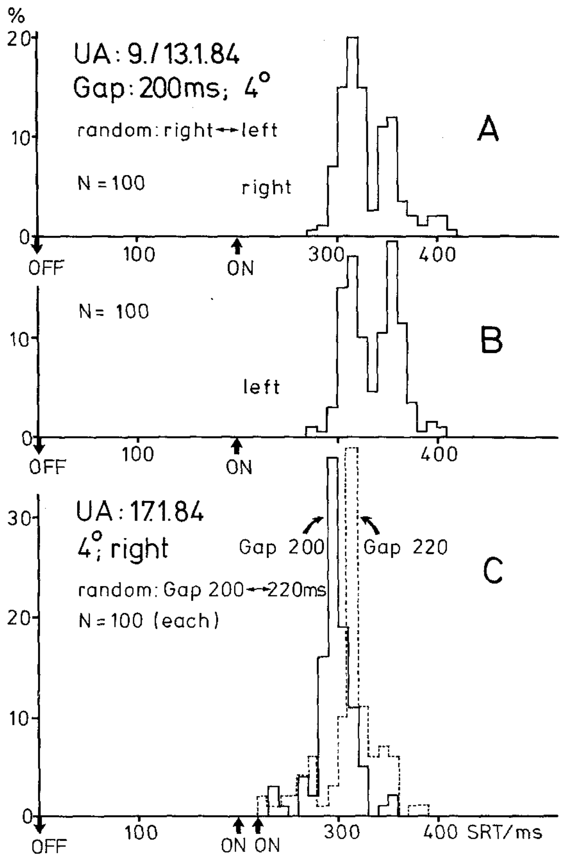

Fig. 2A–C. Same as Fig. 1 but for different conditions. In **A** and **B** the target position was randomly varied between 4° to the right (**A**) and 4° to the left (**B**). Both right and left directed saccades gave a bimodal distribution of their reaction times corresponding to the express and to the regular saccades seen in Fig. 1. In **C** the gap duration was randomized between 200 ms (continuous line) and 220 ms (broken line), while target position was constant. One clearly sees the corresponding shift of the express peak by 20 ms indicating, that the express saccades are timed by the onset of the target. Bin width: 10 ms

results of Saslow (1967) in humans and goes along with our own observations in the monkey (Fischer et al. 1984).

2. *Control experiments*

(i) To rule out the possibility that subjects could predict the time when they had to make the saccade, we randomized the period of fixation, i.e. the time of fixation point offset, yet keeping the gap duration constant at 200 ms. As a result the distributions remained bimodal with the peaks at approximately the same position.

(ii) To further make sure, that the first (100 ms) peak is due to saccades initiated upon target onset we used different gap duration of 150, 200, 220 and 250 ms. In all cases bimodal distributions were obtained with the first peak around 100 ms (from target onset) and the second around 150 ms.

(iii) We also randomized the gap duration between 200 and 220 ms in order to see whether or not the express peak would shift correspondingly. The plots of Fig. 2C clearly show the two peaks separated by 20 ms as expected if the saccades were triggered by target onset rather than by fixation point offset (in which case both peaks should occur at the same position). Therefore, anticipation and prediction cannot account for the existence of the express saccades.

(iv) In control sessions, where subjects were not notified of their reaction times, essentially the same results were obtained.

3. *Stability of the reaction times of express saccades*

The peak around 100 ms in the distribution of the reaction times can be very narrow. Using a standard bin width of 10 ms we often observed that almost all express saccades in a single session had reaction times falling into only 3 neighbouring bins. Moreover, as we repeated the experiment at several days using the same subject the maximum of the peak occurred within the same bin. Even different subjects produced peaks the maximum of which occurred in the same bin (e.g. 91–100 ms).

To further see, how stable the reaction times of the express saccades could be, we reconstructed some distributions on the basis of a bin width of only 5 ms. The subject whose data are shown in Fig. 1 (SK) produced the maximum of the express peak within the same bin, 96–100 ms, at the same or at different days. As we averaged the data from three sessions the distribution of Fig. 1 was obtained. It shows that the population of the express saccades may exhibit a standard deviation below 10 ms. (Note again the clear cut bimodality of the distribution.) The data of two other subjects were analysed the same way. One (UA) reproduced during 4 sessions at 4 different days the maximum of the express peak with a precision of 5 ms at 91.4 ± 7.1 ms; 95.5 ± 10.4 ms; 96.1 ± 8.1 ms and 94.6 ± 8.8 ms. The mean of all 4 sessions was 94.6 ± 8.8 ms. The data of another subject (MG) were almost undistinguishable from those of UA.

The stability of the reaction times of the express saccades is also seen if one compares different subjects. In our population of 12 observers the individual mean values varied between 294 ms and 315 ms. Their individual standard deviations ranged from ±7 ms to ±17 ms. The mean of the means (n =

12) was 303.7 ± 6.9 ms and the mean standard deviation was ±10.8 ms.

The stability of the reaction times of express saccades is contrasted by the much larger variations of the reaction times obtained in a task where the fixation point remains on throughout the trial with all other conditions remaining the same. Under those circumstances reaction times are in the order of more than 200 ms having standard deviations of 30 ms or more (Saslow 1967). We repeated Saslow's experiment in our subjects and confirmed his result.

4. *Further observations*

(i) The amount of regular saccades can be very small for some subjects (see Fig. 2C) and larger for others (Fig. 1). Therefore, to identify the regular saccades for sure one some times has to run an experiment with randomized target positions (see Fig. 2A and B), where the distributions contain usually more regular saccades.

(ii) The mean reaction time of the express saccades can be different for right and left saccades. For example, observer UA had express times of 95 ms in both directions, observer BF (data not shown) produced mean values of 105 ms to the left and 115 ms to the right. The other observers showed no major asymmetries; their express peaks were between 94 and 115 ms. Note, that because of the stability of the reaction times of the express saccades differences of the mean (position of the peak in the distribution) as small as 10 ms can be reliably detected.

(iii) For some observers a third small peak occurred in the distribution (see Fig. 2A and B) at about 200–240 ms from target onset.

Discussion

The identification of the express saccades observed in the monkey with the 100 ms – peak in the distributions of Figs. 1 and 2 relies on the bimodality of the distributions and on the (identical) visual conditions under which they occur. The absolute values – 75 ms in the monkey and 100 ms in humans – must be different in the two species if one assumes similar, if not identical conduction velocities. (For example: a difference of axonal length of 20 cm would account for 20 ms assuming a mean conduction velocity of 100 m/s.) Also, a numerical comparison between monkey and human saccadic reaction times would have to take into account that the express saccade reaction times are very sensitive to the physical parameters of the target and its eccentricity and depend also on the amount of previous training. The mean values range from 68 ms to 120 ms in the monkey (Fischer et al. 1984; Boch et al. 1984).

We have extensively discussed the possible implications of the express saccades for the processes preceding voluntary visually guided rapid eye movements in the monkey (Fischer and Boch 1983; Boch et al. 1984; Fischer et al. 1984). The fact, that express saccades occur when the fixation point is extinguished before the new target appears (gap) together with the observation, that saccades to the same target have reaction times of more than 200 ms when the fixation point remains visible (overlap) has led to the conclusion, that the break of fixation, as a necessary prerequisite for the next saccade, takes a time which is included in the reaction time in the 'overlap' condition but not in the 'gap' condition.

It can be also argued, that it is the time to change the direction of visual attention which adds to the reaction time in one case and not in the other. From our present knowledge there is no possibility to differentiate between these two interpretations. It may even turn out, that breaking fixation without moving the eyes is the process which one experiences as paying peripheral attention or vice versa. We know from single unit studies in the monkey, that neurons in the visual association cortex are more sensitive to light in the absence of a fixation point and can be even activated by the offset of the fixation point in the presence of a peripheral receptive field stimulus (Fischer and Boch 1984). This activity may reflect the animal's attention but could also indicate that the animal has stopped to actively fixate, being ready to move its eye to the target.

Why is it, that express saccades have not been found earlier? There are several possibilities:

(i) Specialists on eye movements might have considered reaction times around 100 ms and below as to short and discarded them as artifacts.

(ii) Randomization decreases the amount of express saccades and the two peaks in the bimodal distribution may be very close to each other particularly for well trained subjects. If one does not look at the distribution using an appropriately small bin width one easily misses the express saccades as a separate population and simply treats the data as a single population with a larger standard error.

(iii) In studies of saccadic reaction times usually a fixation point is used, in which case the chances for express saccades are very small if not zero. To see the phenomenon easily one has to use the gap paradigm.

(iv) Not all subjects may show express saccades under all conditions. Observer BF in our study, for example, produced no express saccades to the left, when the target position was randomized between right and left. He produced, however, quite a lot of express saccades to the right under this condition. Also, to the left he showed a very narrow and large peak of express saccades, but only when the target location was kept constant.

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