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The human brain's algorithm for extrapolating motion, and its possible gender-dependence

Robert Ehrlich*

Department of Physics, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA

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Abstract

Some athletes accomplish feats requiring a timing accuracy 100 times better than their reaction time. This capability implies that the brain can accurately extrapolate the motion of objects. We hypothesize that the brain uses a simple algorithm to accomplish this extrapolation, and that the algorithm is influenced by the subject's gender and recent observations of motion. We describe an experiment in timing the motion of a dot across a computer screen designed to discover the motion extrapolation algorithm. Different types of motion of the dot were studied. The experiment was conducted with 126 college students (two-thirds female), who each performed 1000 trials. By using as many as 126,000 trials, the random noise inherent in individual trials averages out, allowing the underlying algorithm to be revealed. The results show that motion extrapolation is done using the average velocity of a moving object with no correction for changes in velocity during the motion, but with an ad hoc adjustment based on recently observed motions and on gender—males having on average a smaller error than females. A future controlled experiment will be needed to establish whether the observed gender difference is due to the greater experience of males with such related tasks as video games and sports.

Keywords: Motion extrapolation; Gender differences; Visual saccades; Mislocalization of moving targets

The human ability to extrapolate motion is truly extraordinary, as demonstrated for example by the ability of a baseball or cricket batter to time the collision between bat and ball to an accuracy of about 2–3 ms [7]—which is two orders of magnitude less than typical human reaction times [3]. Clearly, given the appreciable delay due to nerve impulse propagation time [9], the brain must accurately extrapolate the motion of bat and ball when it decides when to create the nerve impulses that upon their arrival instruct the muscles to begin the swing.

Previous research has shown that the brain does not merely extrapolate motion based what is seen, but that it uses some kind of algorithm to accomplish its task, and that the algorithm, while resistant to change, is affected by what kind of motion has been observed recently [12]. In the present work we confirm that finding, and we seek to determine the nature of the brain's algorithm by examining the timing errors made when visually observing motion. The data show that when we observe an unfamiliar straight line motion, the brain extrapolates using the average velocity up to the point of extrapolation, with no account taken of any variations in velocity. A more sophisticated algorithm is found to apply when observing repeated motions of a similar type, and the result is smaller timing errors. In the case of unfamiliar motions, the data show a pronounced gender-dependence, whereby males on average make a correction that reduces their average timing error to 40% of females.

The present work was accomplished using a computer programme that generates a spot moving across a computer screen in a straight line in a manner described below. It is based on the results of a class project in which 126 students in an introductory physics class were encouraged to time the motion of the spot as accurately as they could. Specifically, the students were instructed to start the motion of the spot by clicking a mouse on a 'start' button on the screen, and then record the precise instant of its arrival at the line endpoint by clicking the mouse on the 'time'

* Tel.: +1 703 993 1268; fax: +1 703 993 1269.
E-mail address: rehrlich@gmu.edu.

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button. The spot remains continuously visible throughout its motion.

Unlike earlier motion extrapolation research conducted in an experimenter's laboratory, the class project reported here was done by students on their own computers in their spare time—facts which allowed us to collect a very large amount of data (1000 trials for each of 126 students). The large amount of data allows one to glimpse the underlying algorithm in the presence of much noise associated with individual trials, and person-specific systematic errors. The method also allows readers who are academics without their own lab to easily confirm the results reported here by making an assignment to their students in a large class.

The type of motion investigated was such that the position of the dot on the screen at a time t had the following functional form: $x(t) = x_T\,(t/T)^{\gamma}$, where T is the time to complete the motion, i.e., to arrive at x_T, and γ is a constant. Two values of γ have particular significance, i.e., $\gamma = 1$ for constant velocity motion, and $\gamma = 2$ for uniformly accelerated motion, similar to that of a freely falling body. On any given trial T was deliberately randomly changed by up to 40% to ensure that students would not get into a rut of simply clicking the mouse after a fixed time interval on every trial without even needing to watch the moving dot. Students were shown the error dt they made after each timing attempt, and could see whether they clicked the mouse too early (d$t < 0$) or too late (d$t > 0$). There was no reward for obtaining small dt's, but as one incentive to keep making a reasonable attempt despite the tedium of 1000 trials, the computer would only accept the results if the absolute value of |dt| was less than 0.20 s [11]. For some students γ was chosen at random for each trial from the range: $0.5 < \gamma < 2.9$ while for others it was chosen in a sequence from the smallest to the largest value in this range. We refer to these two types of data runs as 'random-γ' and 'sequential-γ'.

For both random-γ and sequential-γ runs, we examine the dependence of dt on γ by grouping the data in 12 equal sized γ-intervals, and showing the average dt for all trials falling within each γ-interval. Let us first consider the random-γ runs in which each trial presents the user with an unexpected type of motion. The results of a random γ run for one typical student are shown in Fig. 1. Note the data points for this student cluster about a fitted straight line with positive slope—a feature seen in nearly all random-γ runs. The value of the slope

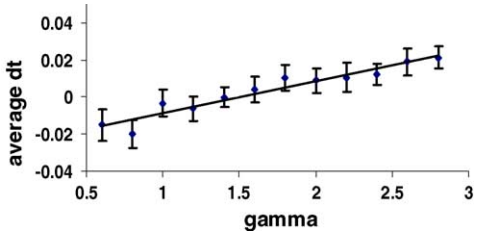

Fig. 1. Average time error dt vs. γ for 1000 trials for a random γ run by one typical student. Data points and error bars are based on grouping the data into 12 equal γ-intervals. The data for most random γ runs are well described by linear fits with similar slopes but dissimilar y-intercepts.

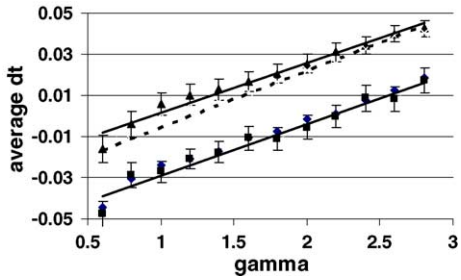

Fig. 2. Collective average time error dt vs. γ for 1000 trials for random γ runs by 18 males – (lower) data, and 38 females – (upper data). Runs for which T fell in the smallest quartile ($T < 0.45$ s) have been dropped. The dotted line shows what the fitted line would look like for females if we had used the median dt (being less sensitive to outliers) rather than the mean values. For males, the median values and the mean values yield indistinguishable fitted lines. The separation in dt by gender averaged over all γ is 4.0 standard deviations.

varied from student to student, but by a significantly smaller amount than the values of the dt-intercepts. In combining the random-γ runs for all students we excluded those cases where the time T was less than 0.45 s (very fast computers), since in those cases the trials took place too quickly to obtain a genuine measurement. The collective data for 56 students who had random-γ runs is shown in Fig. 2 separately by gender for 18 males (lower data) and 38 females (upper data). Collective data points are the average dts for all students for each γ-interval, and the error bars are based on the variance in those means. As can be seen the γ-dependence of dt is extremely linear with virtually the same slope for both genders.

The two fits in Fig. 2 look suspiciously good, given the size of the error bars, which come from the variance of the means for all individuals. The small scatter of the data points is due to the dt-values for the twelve data points being highly correlated, so that combining the data from N persons does not reduce the error bars on each point by $\sqrt{N}$. In fact the size of the error bars for the collective data for 38 females are not that much smaller than the error bars for the one student shown in Fig. 1.

Although the slopes of the fitted lines in Fig. 2 are very similar for males (0.0255) and females (0.0242), the y-intercepts are significantly different. One gauge of the statistical significance of the gender difference is to look at the value of dt (averaged over all γ) for male and female students. The average dt for males is 40% that for females, $\langle \Delta t_M \rangle = 0.4 \langle \Delta t_F \rangle$, and the difference, i.e., $\langle \Delta t_F \rangle - \langle \Delta t_M \rangle = 0.028 \pm 0.007$ s represents a four standard deviation effect, or a two-tailed probability $p < 6.4 \times 10^{-5}$. (Although we are not here measuring a reaction time, the magnitude of the gender difference in average dt, i.e., 0.028 s, by coincidence is consistent with the reaction time difference when spatial stimuli are involved [6]. By comparison when the stimuli have a strong semantic component, females are found to be the favored gender [8].)

Of the 126 students in this study, 56 of them made sequential γ runs rather than random γ runs. Recall that in a sequential-γ run the motion of the dot in each trial differs

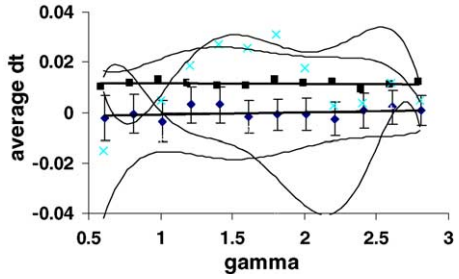

Fig. 3. Collective average time error dt vs. γ for 1000 trials for sequential γ runs by 13 males – (lower straight line fitted data), and 20 females – (upper straight line fitted data). Error bars are shown only for the male students to avoid confusion. The average dt for males is remarkably consistent with zero everywhere. The gender separation is statistically insignificant. The light four curves and points show the dt vs. γ behaviour for four individual students who did sequential γ runs.

only very slightly from the previous trial. Fig. 3 shows the data from four individual students (light curves), and the combined data divided according to gender. For students making sequential γ runs, we see that the combined data were remarkably γ-independent (zero slope fitted lines) for both genders, and consistent with zero dt for all γ. Note that individual student data are not γ-independent, however. For the combined data, males on average had |dt| closer to zero than females (as with the random γ data), but now by a statistically insignificant margin (1.3σ). As with the random γ data, the suspiciously good look of the data (given the size of the error bars) is due to the very high correlation of dt-values for different γ's.

We now discuss a simple algorithm to explain the data for the random γ runs. We assume that the brain sends a signal to the fingers to click the mouse when the observed moving dot has reached that point in its path such that the computed remaining time for it to reach the end of the line equals the estimated time it takes a nerve impulse to reach the fingers, δ. Further, it is assumed that the computed time is based on the brain's judgment of the average velocity of the moving dot up to that instant. The use of the average velocity implies that no account is taken of whether the velocity has been changing up to that point. Clearly, the algorithm yields exactly the right result (d$t = 0$) only when the velocity of the dot is constant or $\gamma = 1$.

Let us see what error dt the algorithm yields for arbitrary values of γ. Given that $x(t) = x_T\,(t/T)^{\gamma}$, the average velocity of the moving dot up to the time $t = T - \delta$ can be expressed as:

$$v = \frac{x}{t} = x_T\left(\frac{T-\delta}{T}\right)^{\gamma}(T-\delta)^{-1}, \tag{1}$$

and the time computed by the algorithm for the last segment is not δ, but instead: $(x_T - x)/v$ leading to an error:

$$\mathrm{d}t = -\delta + \frac{(x_T - x)}{v} = -\delta + (T-\delta)\left(\left[\frac{1}{1-\delta/T}\right]^{\gamma} - 1\right) \tag{2}$$

Furthermore, since $\delta/T \ll 1$, we have that

$$\left(\frac{1}{1-\delta/T}\right)^{\gamma} \approx 1 + \gamma\left(\frac{\delta}{T}\right), \tag{3}$$

and hence finally:

$$\mathrm{d}t \approx (\gamma - 1)\delta \tag{4}$$

According to Eq. (4), we predict the γ-dependence of dt to be a linear one, with d$t = 0$ for $\gamma = 1$. This predicted behaviour is exactly what is observed for random-γ trials for females (see Fig. 2). The value for δ is just the slope of the fitted line, i.e., $\delta = 0.0242$ s for females. The only significant difference found in the algorithm for males is that they make an adjustment by starting the nerve signal earlier by 0.028 s compared to the females for all γ values. The effect of this adjustment is to bring the value of dt averaged over all γ values much closer to zero for males. The magnitude of the adjustment needed may be unconsciously learned by males as a result of the feedback received when they see the sign of dt on a succession of recent trials done with various γ-values.

We suggest that females also make a similar ad hoc adjustment, but only after many trials at almost the same γ are observed, i.e., when doing sequential γ runs. This conjecture is based on the observation that both genders give virtually γ-independent results for dt (Fig. 3), when the data is combined for many individuals doing sequential γ runs. Based on Fig. 3, males seem to be able to make the ad hoc adjustment extremely accurately, so that for all γ we find d$t \approx 0$ within a margin of several milliseconds, while for females there may be a small residual error. Thus, for both the random-γ and sequential-γ runs males appear to have smaller timing errors, dt, with the gender difference only being statistically significant in the former case. The γ-independence of dt found for sequential-γ runs suggests that as a result of experience with many slowly changing γ trials, the brain continually updates an adjustment to the value of dt as it extrapolates motion. Note, that the brain is not simply taking some average acceleration into account, because that would give the d$t = 0$ only at $\gamma = 1$ and $\gamma = 2$, and depart from zero elsewhere by an observable amount [5].

The notion discussed here that males and females use different strategies in performing timing tasks agrees with the findings of Adam et al. [1], who found that the two genders had average reaction times that varied by a statistically significant amount ($p < 0.05$) with respect the left-right location of a visual stimulus. As with our results, Adam et al. also found that males on average tended to respond earlier than females [1]. It must be remembered, however, that all such gender differences hold only on the average, and that individual females may yield smaller timing errors than the average for males. Furthermore, it is unclear based on the present work whether the gender difference might be learned rather than innate, and whether it might be a proxy for something else, such as greater male experience with video games or sports. Nevertheless, the difference reported here does conform both to the

greater skill on average of males in certain sports requiring very accurate timing ability (such as ping pong, baseball and basketball). It may also be related to the reported greater size and asymmetry in males of the inferior parietal lobule—the part of the brain linked with one's ability to estimate time, judge speed, visualize the world three-dimensionally and do mathematics [2].

For the results presented here to be meaningful, it is important that they not depend on any characteristics of the computer on which the programme is run. Two particular computer properties are of particular importance: the mouse interface and the computer speed. On some computers the mouse interface polls the mouse at a specific frequency f(Hz), rather than being interrupted whenever a mouse click occurs. This has the effect of yielding dt values that are quantized in multiples of $1/f$ s. In contrast, on computers having the interrupt type of mouse interface, the dt data showed no quantization. In a few cases students fortuitously switched computers midway through a run of 1000 trials from a computer with quantized dt to one with unquantized dt. If quantization of dt had a systematic effect on the value of dt one would expect to see an abrupt change in the average dt-value occurring at the γ-value where a student switched computers. In fact, no abrupt discontinuity in the graphs of dt versus γ was observed at the switching point in these cases, which suggests that the quantization effect seen on some computers is not a reason to discard those runs.

The other computer property that might affect the results is processor speed. In fact, the time T for the spot to complete its motion varies considerably: $0.2\,\text{s} < T < 3.0\,\text{s}$, depending on the computer speed. When the data were examined in four quartiles of time T, the data for the shortest quartile ($T < 0.45$ s) had a much smaller dt versus γ slope of the fitted line than the other three quartiles, whose slopes were quite consistent with one another. This smaller slope for the fitted line for the data in the shortest T quartile is an artifact, since many of those runs were simply too short to yield a reliable time for any γ, and they had to be discarded, as explained earlier. Thus, in summary, the conclusions drawn from the data used in the analysis are independent of both the type of mouse interface and the computer speed. One other computer-dependent quantity, i.e., the refresh rate of the monitor seemed to play no role, in that the flicker rate is simply too high to notice visually.

There are several alternate interpretations of the results regarding the gender differences reported. One possibility is that males and females merely prefer to use different strategies in judging speed and time of arrival of the dot, with males indifferent to the sign of small errors, while females tend to be "conservative," i.e., they prefer to be sure that the dot arrival has occurred before clicking the mouse. It is possible that this interpretation could be tested through interviews of the participants after the experiment, or with more explicit instructions as to how to perform it.

A second alternative explanation relates to the uncontrolled nature of the experiment, whereby no attempt was made to take into account variations in other variables. There are many variables which were not controlled for, such as light conditions, time of day, disturbing or distracting influences, which would seem unlikely to affect the gender-dependence of the results reported. On the other hand, there are other gender-correlated variables, such as handedness, muscular strength, experience with video games and sports, which might show very significant differences between the genders. Given the nature of the task at hand, which is quite similar to a video game, it seems plausible that males who tend to have greater experience in this area would excel because of that fact. A controlled experiment might have matched only males and females that had equal experience with video games or sports. On the other hand, were such a comparison to yield a negative result for the gender difference, it would leave unanswered whether males have greater experience with video games because they tend to have a greater ability in timing tasks. Consequently, the author believes that while a repeat controlled experiment might have considerable value, the "uncontrolled" approach reported here also has value, because of the ease in accumulating large quantities of data, and because students performing the experiment on their own are less anxious about it compared to their doing it in a laboratory.

There are several other well-established lines of research related to the present work. One concerns the "flash-lag effect," whereby a moving target is mislocalized when it is flashing [10]. In the present work, although one sees discontinuous images appear sequentially on the screen, they are close enough in time, so that one does not perceive distinct flashes. A second related line of research concerns saccades or rapid eye movements designed to bring the image of a moving object into the fovea as quickly as possible, which is distinct from the smooth pursuit eye movements that then track the object. Nevertheless, because it takes time to generate a saccade, the saccade system does need a velocity signal as input to compensate for the motion of the object so as to keep its image at the fovea during the saccade [4]. A variety of neural mechanisms have been proposed for generating such saccade inputs, which involve the firing of one or more speciifc neurons [4]. Some of these mechanisms may well also be responsible for the results reported here.

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