Changes in saccade kinematics associated with the value and novelty of a stimulus

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Abstract—**The kinematics of elementary movements such as saccadic eye movements are highly regular across repeated movements and across individuals. Historically, saccades have been viewed as following a fixed kinematic pattern with a characteristic peak velocity and duration that varies only with the amplitude of movement. Here we show experimentally in humans that saccade peak velocity and duration can be modulated through presenting stimuli of differing intrinsic value, and that repetition of the same stimulus leads to a decline in saccade speed which we interpret as a decline in the value of that stimulus. Surprisingly, we find that, among saccades of comparable amplitude, faster movement is associated with lower variability - contradicting the idea of a speed-accuracy tradeoff. We consider these results in the context of theoretical models that attempt to account for saccade durations through balancing costs that penalize accuracy with costs that penalize movement duration.**

I. INTRODUCTION

Why do movements have a particular duration? One factor that influences duration is movement amplitude. Larger movements typically have longer durations, and this relationship has been well-documented in the case of rapid eye movements (also known as saccades) [2], [1]. The so-called 'main sequence' of eye movements describes how saccades of both human and non-human primates exhibit a stereotyped increase in velocity and duration with increases in movement amplitude. This relationship can be explained through control-theoretic models in which one assumes that movements are programmed to minimize a combination of an accuracy penalty and a time penalty. For example [4] proposed a cost of time that is proportional to movement duration. It is beneficial to move more slowly in order to achieve higher accuracy, but it is also in the subject's interest to move more quickly so as to avoid the rising cost of time. The appropriate duration is the one that optimizes

this trade-off. This model provides a good fit to main sequence data for small-amplitude saccades. However, this model underestimates the duration of large-amplitude saccades.

A newer model has been proposed to account for the discrepancy between prediction and data for eye movements of amplitude 40-deg and higher [9]. This new model employs a different cost on time: namely, a cost that rises in a hyperbolic fashion. The hyperbolic time cost states that the cost of time rises more quickly for movements of short duration than those of long duration. The changing rate of the time cost enables the new model to reproduce the main sequence for saccades of all sizes. Larger amplitude saccades, which are necessarily longer in duration even under a linear time cost, can afford to take even longer due to the less stringent time cost at longer durations using a hyperbolic time cost.

Saccade duration, however, has more recently been shown to depend on factors besides saccade amplitude. In one experiment monkeys were trained to make saccades to targets at four different locations [10]. One of the four targets was associated with a juice reward while the others were not. Saccade speeds were higher and durations lower to the targets associated with reward despite the fact that all saccades had the same amplitude. In another experiment, humans made saccades to a target with the knowledge that they would be rewarded with an image [11]. Movement speeds were higher when the image was a face than when the image was noise. These results contradict the idea of a main sequence in which saccades are simple stereotyped actions. Instead one should view saccade generation as the result of a sophisticated decision process whereby different costs are weighed against one another in order to determine the best possible course of action. Models based on control theory can naturally be extended to accomodate stimulus value, enabling them to predict the phenomenon of faster

movements to more rewarding targets [9].

Conversely, we expect that we can infer the intrinsic value of a stimulus to a subject based on the speed with which the eye moves towards it. We performed an experiment to further investigate the relationship between the reward associated with a movement and the corresponding movement speed. We expect that, if a movement carries a particular value, then that value should change according to how many times the particular stimulus has been observed. In other words, does repeated exposure to a rewarding stimulus result in a decline in movement speed? If so, what can be inferred about how the brain assigns a value to the stimulus and its relation to the generation of motor commands?

II. METHODS AND MATERIALS

A. Experimental Setup

For our experiment, we recruited n=6 healthy volunteers (mean age 23, range 18-26, 3 females). Subjects sat in a dark room in front of a CRT monitor (36.5 x 27.5 cm, 1024 x 768 pixel, light grey background, frame rate 120 Hz) with head restrained using the combination of a dental bite bar and a forehead rest. Targets displayed on the screen were either black dots of 2-deg diameter or face images of roughly the same size. All targets were displayed with the use of the Psychophysics Toolbox (PTB-3) and Matlab version R2006a. The screen was placed at a distance of 31 cm from the subject's face, and an Eyelink 1000 (SR Research) infrared camera recording system (sampling rate = 1000 Hz) was used to record movement of the right eye.

Figure 1 provides an overview of the experimental protocol. Participants were asked to make saccades between targets with a horizontal separation of 40 degrees and positioned symmetrically about the center of the screen. Each saccade was cued by the appearance of one of two possible targets, having a vertical separation of 5 deg. The previous target remained on the screen until the gaze position was within 3 deg of the new target. Thus there was some period of time (reaction time plus movement time) when both targets were on the screen at the same time. After an initial training period, subjects completed 12 blocks of 80 trials. Each trial consisted of three parts: inter-trial interval, reaction time, and movement time. The inter-trial interval was set to 1000 ± 50 ms throughout the entire experiment.

There were three block types with different target presentations. In one block, all of the targets presented were dots; in the second block, the initial and final 10 targets were dots and the middle 60 were identical
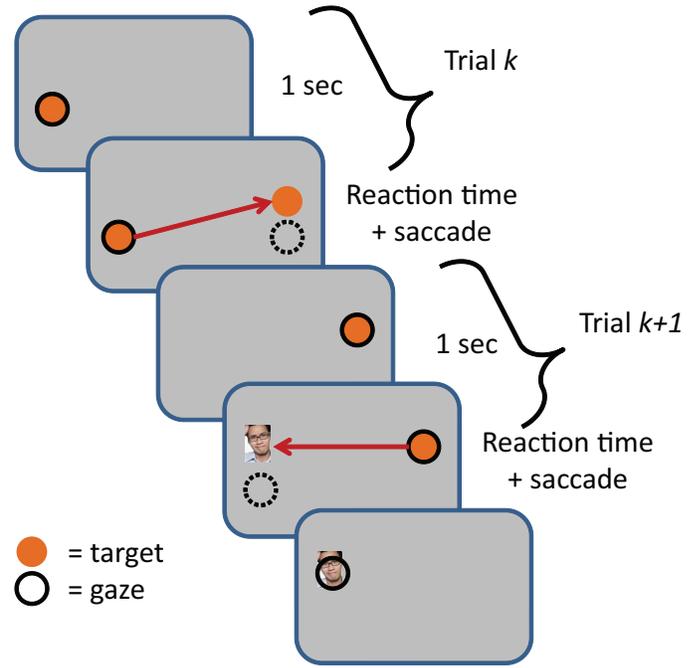
Fig. 1: Experimental Design

images of a face; in the third block, the middle 60 trials were random images of different faces. Block types were presented in a different, pseudorandom order for each subject.

B. Data Analysis

All data analysis was completed off-line using Matlab R2011a (Mathworks). The gaze position data were filtered using a 2nd-order Savitzky-Golay filter with a half-width of 27. Calibrations of gaze position in pixel space relative to the raw pupil coordinates were performed off-line from data at the beginning of each block. Saccade beginning and end were marked using a 20-deg/sec velocity threshold. For the purposes of analyzing saccade endpoint variability, movement endpoint was marked after saccade velocity was below 5-deg/sec for a hold period of 100 ms. Reaction time was determined by comparing the time of saccade initiation and the target appearance time in each trial.

Five criteria were used to assess saccades: (1) Amplitude between 35 and 45 deg. (2) Duration between 50 and 350 ms. (3) Reaction time between 100 and 1000 ms. (4) No blinking during the saccade. (5) Saccade velocity profile exhibits only one maximum. Any saccade that did not meet all five criteria was excluded from the analysis (average 6.4 percent of all saccades). Peak velocities were normalized separately for leftward and rightward saccades by dividing by the mean peak velocity during

the first 10 trials across all blocks. The normalized peak velocity was then averaged across all four repeats per block per subject and across all subjects. Saccade endpoint variability was normalized in a similar fashion, whereas reaction time was normalized for leftward and rightward saccades combined. We assessed the effect of changing target type on the averaged variables of interest with an analysis of covariance at a significance level of 0.05.

III. RESULTS

A. Stimulus type influenced saccade kinematics

Our experiment addressed the question of how the brain alters movement kinematics in response to repeated stimuli with different values. Two of the three block types included a long series of trials with the same stimulus, whereas one block type had no such series. Operating under the assumption that the act of foveating a novel target is rewarding, then the block with no series of repeats should be more rewarding than the other two. Figure 2a shows the change in peak velocity averaged across all subjects from beginning to end of each block type. There was no significant difference across block types ($p = 0.87$) between average peak velocities during the 10-trial beginning and ending series (in which the stimulus was always a dot). The most appreciable difference in velocities came right after the transition to the middle portion of the block, when the target changed from dot to face. During the block with repeated dot targets, peak velocities declined during the entire middle portion of the block - a phenomenon that is well-documented [11]. Both the single-face and multiple-face blocks saw sharp increases in velocity of order 3 per cent upon onset of face image trials followed by a steady decline. The velocities during the multiple-face block remained highest throughout the middle 60 trials, supporting previous results that stimulus type affects movement speed [11].

The decrease in velocity during the block was accompanied by increased movement duration. However, differences in duration across block type were not as clear as differences in velocity, suggesting that the velocity profile shape changes. For instance, the 3 per cent increase in velocity observed upon introduction of face images was accompanied by a 2 per cent decrease in duration. Changes in reaction time were also much less noticeable than those in peak velocity (Figure 2b). However, there was an effect of block type on the rate of change in reaction time during the middle portion of

(a)

(b)
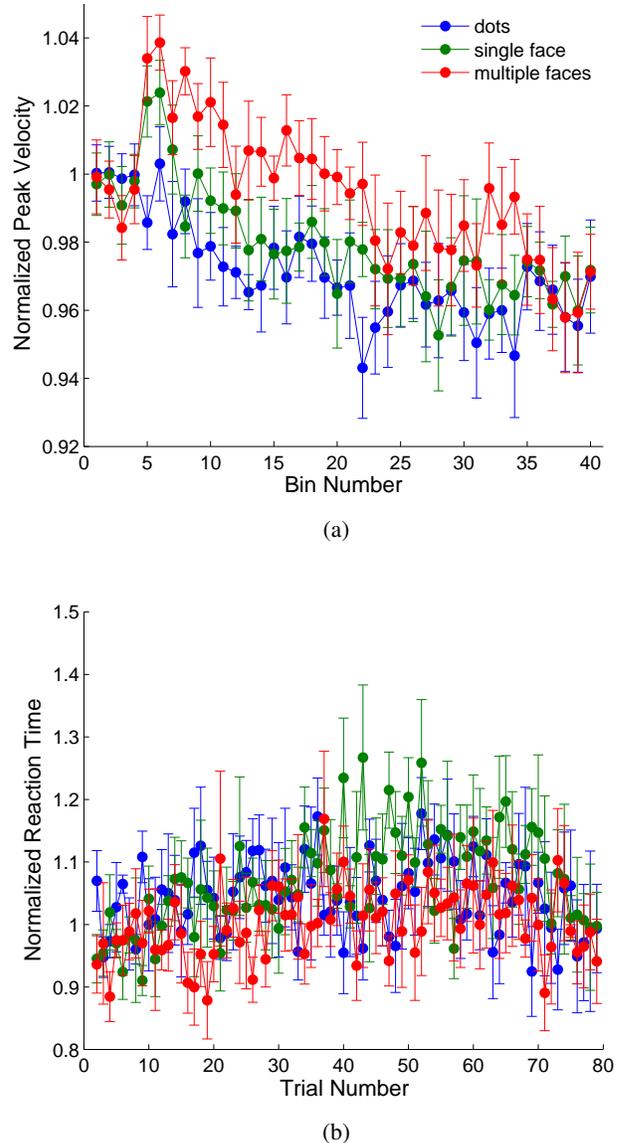
Fig. 2: (a) Mean normalized changes in peak velocity over the course of a block for each different block type. (b) Mean normalized changes in reaction time within blocks. For both panels, Red: different face presented on each trial, Green: same face presented on each trial, Blue: same dot presented on each trial. Error bars represent ± s.e.m.

the block ($p < 0.01$), with faster saccades typically also associated with shorter reaction times.

B. Endpoint variability decreased as saccade peak velocity increased

Regardless of block type, endpoint variability increased during the block; moreover, variance was gener-

ally lower for saccades made to random faces ($p < 0.01$). Figure 3b shows the average change in variance as a function of change in peak velocity. Velocity and endpoint variance were negatively correlated ($r^2 = 0.47$, $p = 0.0001$). It is important to note that both the dot and face images had a diameter of 2 deg, and thus target size cannot provide an explanation for the observed relationship between velocity and variance. One might wonder if the changes in velocity were due to changes in saccade amplitude. There was indeed a significant effect of block type on saccade amplitude ($p = 0.025$). However, average across-subject amplitudes ranged between 39 and 41 deg. Thus this amplitude effect was too small too account for the observed changes in peak velocity within the conventional main sequence of saccades.

IV. Conclusions and Discussion

It has already been established that stimulus type affects saccade speed [11]. However, the change in velocity recorded in this study (3 per cent) is two-fold larger than changes reported previously. Additionally, we looked at the effect of altering the properties of a face image versus using the same face image on the decay in movement speed. We found no significant difference in the rate of decay of velocity to changing face stimuli versus a constant stimulus. All participants' vision was adequate to differentiate different face images from a single face image. Thus it appears that stimulus value has a consistent effect on movement speed, whereas the novelty of the stimulus had no such effect within the context of this study. It is still possible that, given a dataset with more power, the decline in velocity will be significantly less than a situation in which a valuable stimulus simply repeats.

Why is it plausible that stimulus novelty would affect movement speed? Evidence has already been given which suggests that the brain estimates reward for a history of movements [7]. In addition, midbrain dopamine neurons encode differences between actual reward and predicted reward [5]. It is possible that the brain encodes stimulus novelty in a way similar to how it encodes stimulus value. One way to assess this question would be to design an experiment with a shorter block length but a larger number of repeats, as the most enlightening portion of the data occurs upon the change in stimulus from dots to faces.

Another significant finding of the current study is the observed inverse relationship between movement speed and variability. This trend in the data contradicts the
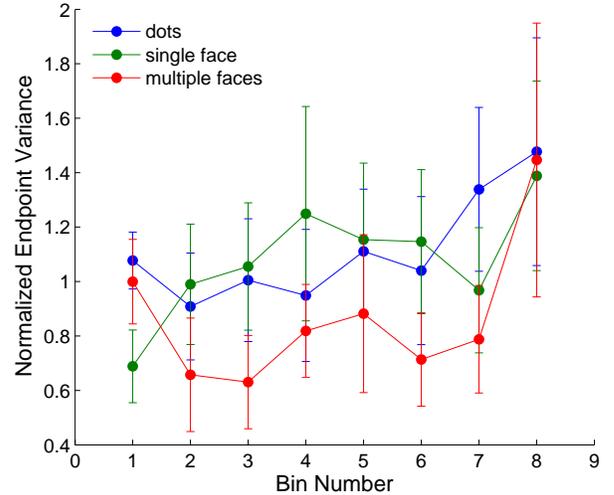
(a)
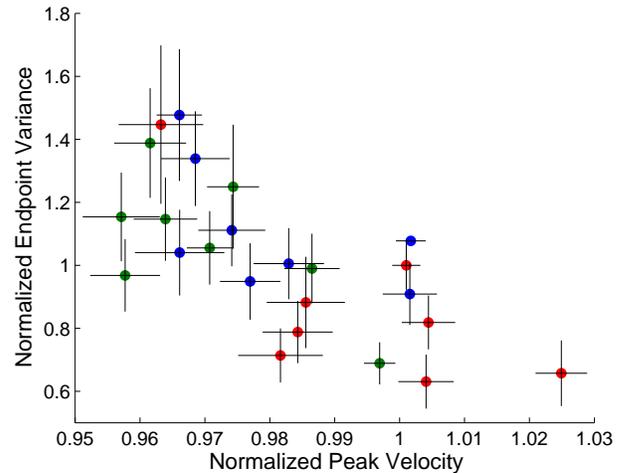
(b)

Fig. 3: (a) Mean normalized saccade endpoint variability within blocks. Each bin represents mean within-subject variance in a bin of 10 saccades. (b) Mean saccade endpoint variability as a function of mean peak velocity for each bin. For both panels, Red: different face presented on each trial, Green: same face presented on each trial, Blue: same dot presented on each trial. Error bars represent $\pm$ s.e.m.

idea of a speed-accuracy trade-off that underlies all computational models that predict movement duration [3]. In our data, we see speed and accuracy improving simultaneously. Previous studies have noted a similar finding of increasing accuracy with speed [10]. Our findings not only reiterate this result, but show that this effect is modifiable in a continuous manner, rather

simply reflecting two distinct motivational states, as suggested by [10]. The extent to which an upcoming movement may offer reward may drive this modulation of the relationship between speed and variability. One can envision speed and accuracy not as having a fixed relationship with one another, but as having a flexible trade-off, lying on a surface whose slope changes along a third axis. It is possible that changes in stimulus value allow, or make it worthwhile to shift to a different point on this third axis. Presumably, this third axis carries its own cost, possibly due to increased attentional demands.

The question remains as to why eye movements have a particular duration. Movement amplitude certainly plays a role. From a theoretical standpoint, this can be explained in terms of a trade-off between increased effort and variability incurred when moving quickly and a decreased cost of time [4], [9]. We have shown that there are other factors that affect movement duration, including stimulus properties such as value and novelty. This suggests that the cost of time may be related to the value of a stimulus. Studies in psychology show that humans discount future reward in a hyperbolic manner [8], [6]. This cost of time in decision making is directly analogous to the cost of time we have proposed for movements. In fact, populations that show a systematic decrease in the cost of time for decision-making (e.g. the elderly) also exhibit slow movements [9]. Our hypothesis is that the neural mechanisms underlying temporal discounting and the control of movements are linked. Such a link could potentially enlighten our understanding of both decision-making and the principles that the brain employs to generate movements.

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