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Effects of stimulus-response uncertainty on saccades to near-threshold targets

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Abstract Kveraga et al. (2002, *Exp Brain Res* 146(3):307–14) reported that saccade latencies are immune to the effects of stimulus-response uncertainty and constitute one of the few response systems that violate Hick's law. Similar effects have been reported for key-presses triggered by vibrations of the fingertips, but robust uncertainty effects were subsequently revealed using weak, low-frequency vibrations (Ten Hoopen et al. 1982, *Acta Psychol* 50:143–157). We wondered whether immunity of saccadic responses would demonstrate a similar intensity-dependency and therefore re-examined the effects of response entropy on saccade latencies using near-threshold visual stimuli. Saccadic latencies remained independent of stimulus-response uncertainty, indicating that saccadic motor programming is unaffected by the duration of the target detection process.

Keywords Eye movements · Response selection · Detection thresholds

Introduction

Stimulus-response uncertainty (S-R uncertainty) is a state in which the responder cannot predict which of two or more responses associated with particular stimuli will be required. S-R uncertainty typically exerts a cost on performance, increasing response latency and decreasing response accuracy. This cost tends to rise as a logarithmic function of the number of stimulus-response associations one potentially has to execute, a relationship

that became known as Hick's law (Hick 1952). We have shown recently that visually-guided saccades are immune to the effects of S-R uncertainty (Kveraga et al. 2002). Specifically, the latencies of saccades do not increase with the number of potential saccade targets. This includes the step from one target to two targets, violating the virtually universal finding that simple RTs are executed faster than choice RTs. Saccades are one of very few response modalities that demonstrate this degree of insensitivity to S-R uncertainty. Smooth pursuit eye movements likewise are not susceptible to S-R uncertainty effects (Berryhill et al. 2004). One feature that these modalities have in common appears to be high compatibility between stimuli and their corresponding responses. High stimulus-response compatibility appears to reduce or eliminate S-R uncertainty effects. It may develop naturally, or it can, in certain cases, be achieved with extreme overlearning in the laboratory (Seibel 1963).

A widely cited example of another highly S-R compatible modality reportedly immune to S-R uncertainty was a study by Leonard (1959) in which subjects pressed keys in response to vibrations applied to their fingers. However, a more extensive study of this task employing vibrations of various frequencies and amplitudes showed that the lack of S-R uncertainty effects is seen only with vibrations above certain thresholds (Ten Hoopen et al. 1982). Any combination of vibration parameters involving higher amplitude (135 μ) and/or higher frequency (150 Hz) stimuli resulted in reaction time (RT) means whose slope over the range of S-R uncertainty levels was very close to zero. Yet weak (15 μ amplitude), low-frequency (40 Hz) vibrations revealed robust S-R uncertainty effects.

Ten Hoopen et al. (1982) interpreted their findings as reflecting varying degrees of ideomotor compatibility—the similarity between the stimulus and the sensory feedback received upon executing the action. Small-amplitude, low-frequency vibrations activate only the cutaneous receptors (Meissner corpuscles), while high-amplitude and/or high-frequency vibrations activate

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both Meissner corpuscles and subcutaneous Pacinian corpuscles—as would the act of pressing buttons. Thus, according to Ten Hoopen et al. (1982), using high-amplitude and/or high-frequency vibrations results in high ideomotor compatibility between the stimuli and the sensory feedback from the responses, which in turn produces immunity to S-R uncertainty.

Although saccades to visual targets do not have this type of relationship, the immunity to S-R uncertainty may nonetheless be dependent on stimulus strength (Kveraga et al. used bright, highly salient “popout” targets). Luminance has a strong effect on the magnitude of visual responses, which influences the time course of visual detection (Hughes and Kelsey 1984; Mansfield 1973) and in turn may have a cascading influence on the time-course of response preparation and initiation (Salzman et al. 1992; Dorris and Munoz 1998; Kim and Shadlen 1999; Gold and Shadlen 2000, 2003). Thus, we wondered whether low-luminance stimuli would introduce a S-R uncertainty effect in human observers. At the very least, we expected that near-threshold targets would prolong the time-course and decrease the probability of visual detection. However, such weak signals might also influence later processes associated with response selection and parameter programming. In this case, the combination of variation in both signal strength and S-R uncertainty might produce interactive effects on saccade latencies that were not observed using high luminance suprathreshold targets alone. The present experiment therefore examined the joint effects of signal strength and S-R uncertainty on the latency and metrics (gain, amplitude and peak velocity) of saccadic eye movements. We employed three target luminances, ranging from very bright to very dim, and three S-R uncertainty levels (one, two, and four possible target locations) in an attempt to answer this question.

Methods

Subjects

Three subjects participated in the study. All were healthy Dartmouth College students or staff and all had normal or corrected-to-normal vision. The subjects were naive with respect to the purpose of this investigation. Each subject was informed about the nature of the recording procedures, the nature of the psychophysical task, and each signed an informed consent document. The Dartmouth College Committee for the Protection of Human Subjects approved the experimental protocol followed in this report.

Stimuli

All stimuli were presented on a computer-controlled video monitor at a viewing distance of 57 cm. The set of

possible spatial locations where the saccade targets could occur were indicated by white 1° annuli located 11° of visual arc from the central fixation point. The rim thickness of the annuli was 1 pixel (4.5 arc min) at a luminance of 25.9 cd/m². Thus, the appearance of four annuli indicated that the target could occur in any one of the four indicated locations, two annuli indicated there were only two potential target locations, and one annulus informed the subject of the exact location of the upcoming visual target. The targets themselves consisted of a luminous disk that filled one of the annuli with one of three different luminance values: 1) “bright”, a maximal grayscale value of 25.9 cd/m²; 2) “dim”, 0.69–0.84 cd/m²; or 3) “very dim”, 0.45–0.69 cd/m². The bright targets were very similar to the ones used by Kveraga et al. (2002).

The grayscale values for the “dim” and “very dim” luminance levels were determined individually for each subject during an initial procedure that occurred before the formal experiment began. In this preliminary procedure, subjects viewed a display that was identical to the one used to convey maximal location uncertainty in the formal experiment. It consisted of four peripheral annuli positioned at the corners of a 24°×24° square (see Fig. 1). These annuli indicated the locations where visual targets could appear. The targets consisted of a luminous disk that filled the internal area of one of these locations. The subjects were instructed to maintain fixation at the fixation disk located at the center of the screen and their eye position was monitored to insure that their gaze remained steady. Both target luminance and target location varied and the subjects indicated whether or not they had detected the target by depressing one of two response keys. The goal of this preliminary procedure was to determine the detection threshold for each subject under conditions that approximated those used in the main experiment. We first estimated the subject’s detection threshold using a staircase method—the luminance increased if the subject reported not seeing the previous target and decreased on the next presentation when they indicated they had seen the target. We then used the method of constant stimuli to get a more precise estimate of the threshold. We tested six luminance values that were distributed around the initial threshold as determined by the staircase method using a discrete trials procedure (30 trials/luminance value). On each trial, a target appeared at one of the locations indicated by the annuli and the subjects indicated whether they had or had not detected the target by depressing one of two response keys. These responses were made without any time pressure. The resulting psychometric functions were used to select the luminance value that supported an 80% detection rate for each subject (designated the “very dim” targets), and a second value two steps higher on their psychometric function (designated “dim” targets, ~95% detection rate). These luminance values were then used in the formal experiment using the same type of display.

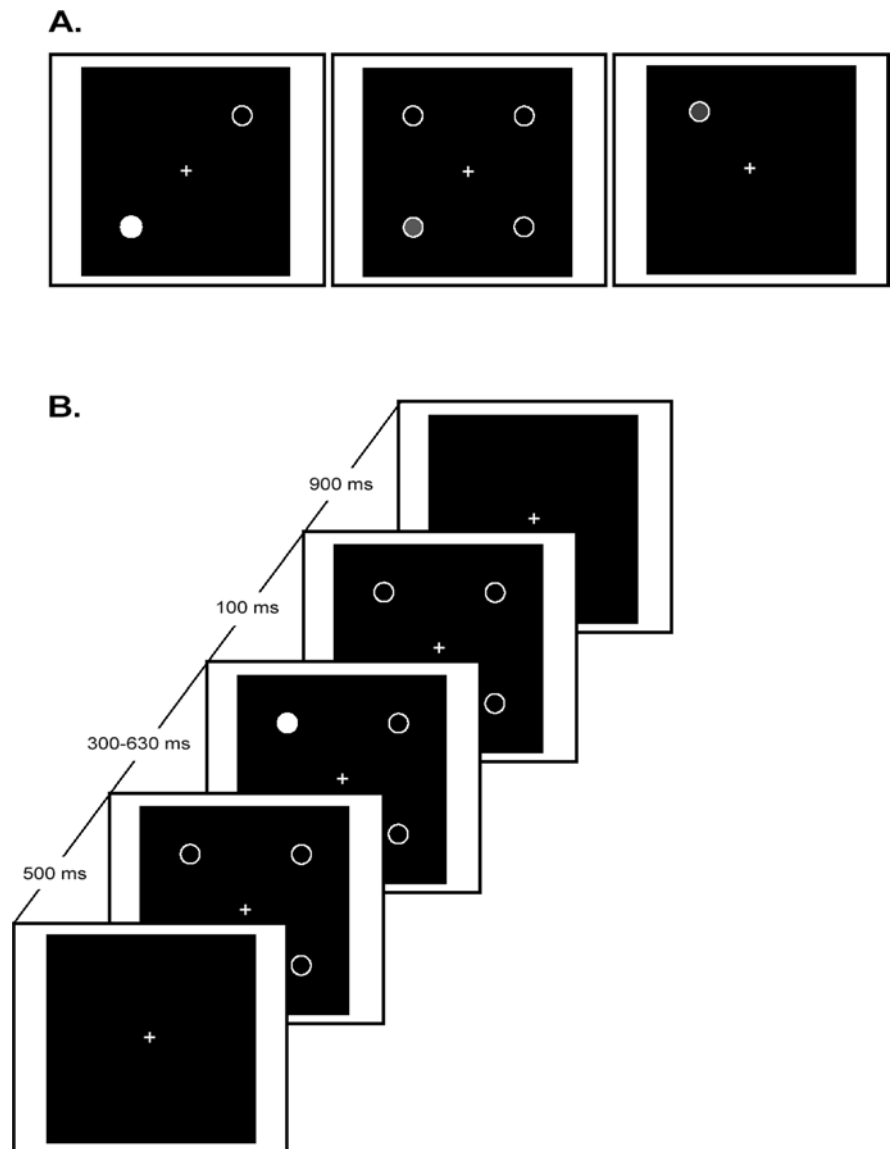
Procedure

Just like the procedure used to determine the detection thresholds, the markers served as cues indicating to the subject the locations where targets could appear. Four annuli meant the target could appear at any one of the four locations with equal probability, two markers meant there were only two possible locations, and one marker meant the subject knew in advance where (but not exactly when) the stimulus would appear. The same procedure was used by Kveraga et al. (2002). The background luminance of the CRT monitor was very dark ($<0.17 \text{ cd/m}^2$), and was surrounded by a white frame (25.9 cd/m^2). The white frame was used to control the adaptional state of the observers by minimizing the fluctuations in space-averaged luminance that would otherwise co-vary with changes in the number of position markers used to indicate the level of S-R uncertainty (one, two or four luminous markers).

The level of S-R uncertainty (one, two or four possible locations) remained constant over a block of 16 trials, and subjects participated in four or five experimental sessions consisting of 18 blocks (six for each S-R uncertainty level) of 16 trials each. The sequence of S-R uncertainty conditions was counter-balanced across subjects and across experimental sessions such that, at the end of the experiment, each subject accumulated a total of 1152–1440 trials, providing between 128–160 trials per the S-R uncertainty/luminance level observation cell.

Prior to each block of 16 trials, the subjects read instructions printed on the display monitor that told them the level of S-R uncertainty for that block of trials. The number and positions of location markers also provided a constant reminder of the set of possible target locations in effect during that block of trials. When the S-R uncertainty level was four, the markers appeared at the four corners of an imaginary square, and subjects

Fig. 1 A Examples of the S-R uncertainty and luminance conditions: *left* the bright, two-target condition; *middle* the dim, four-target condition; *right* the very dim, one-target condition. **B** The trial sequence used in the experiment



were told that targets could appear at any one of the four locations with equal probability. When the S-R uncertainty level was two, the markers occurred at either the positive or negative diagonals (again, with equal probability and counter-balanced across subjects). When there was no S-R uncertainty, a single marker appeared at one of the four corners (constant for that trial block but counter-balanced across testing session and subjects). Target *luminance* varied randomly within each block of trials, with presentation probabilities of 0.50/0.25/0.25 for the bright, dim and very dim levels respectively. These stimulus probabilities were selected because the dim and very dim targets looked virtually indistinguishable (though, of course, they produced discriminable differences in performance) and we wanted to ensure that the subject's motivation remained high by making certain that half of the trials presented easily detectable targets.

Experimental trials lasted 3 s each (including the inter-trial interval). The target duration was 100 ms and prevented the subjects from engaging in overt visual search. The subjects were also told that the first saccade they generated would count as their response, so they should only direct their gaze to locations they thought a target had appeared. Figure 1A shows examples of the various S-R uncertainty and target luminance configurations. The sequence and timing of events within a trial is shown in Fig. 1B. Stimulus presentation was managed by a low-level subroutine that controlled the refresh rate of the display and yoked the timing of all critical intervals and signal pulses to it. All stimuli were drawn with a single screen refresh.

Subjects had to respond within 800 ms of target onset for the saccade to be counted as a valid response. Virtually all responses fell within this window. The saccade endpoint had to land within a 3° window around the target for the saccade to be counted as correct. Both before testing, and again in written instructions displayed on the CRT screen before each block, subjects were reminded that their task was to respond "as quickly and accurately as possible". The instructions were identical to those given to the subjects that participated in experiments reported by Kverega et al. (2002). Eye position was recorded using the scleral search coil technique (Robinson 1963) using the same procedures, equipment, saccade detection criteria, and data analysis techniques described in Kverega et al. (2002).

Results

In the "dim" and "very dim" conditions, our subjects generally either saw the target and responded to it within the allowed time window, or missed the target altogether and never broke fixation during that particular trial. In the bright target conditions, the subjects nearly always made correct and timely saccades. Responses within the allowed time window occurred in 66.5% of the trials for the very dim targets, 92.1% of them for the dim targets,

and 99.8% of them for the bright targets. These were evenly distributed across the S-R uncertainty conditions. Correct responses—saccades that were within the allowed time window *and* met our accuracy criterion (landing within a 3° window around the target) occurred in 62.2% of the trials for the very dim targets, 89.8% for the dim targets, and 97.0% for the bright targets. Thus, only about 3% of timely saccades in each luminance condition were made to the wrong location. This underscores the fact that failures in target detection, most of which occurred in the very dim target condition, typically resulted in no response rather than an incorrect response.

As expected, saccade latencies increased with decreasing target luminance. A repeated-measures ANOVA confirmed a significant main effect of luminance, $F_{(2,4)} = 18.6$, $p < 0.01$ on response latencies: saccadic RTs increased with decreasing stimulus luminance for all S-R conditions. Post hoc Bonferroni comparisons showed that latencies were significantly different for each luminance (all at the $p < 0.01$ level). Importantly, S-R uncertainty had no effect on RTs in any of the luminance conditions. There was no effect of S-R uncertainty ($p > 0.32$) and no significant interaction of stimulus luminance with S-R uncertainty ($p > 0.12$). These results are displayed in Fig. 2.

It is important to note that the percentages of correct saccades did vary slightly with S-R uncertainty, but only for low luminance targets. Paradoxically, detection rates for the near threshold targets showed a slight benefit of position uncertainty. The saccadic detection rates were 57.3%, 61.9%, and 67.5% for one, two, and four possible target locations using very dim targets, whereas the corresponding values for dim targets were 87.6%, 89.9%, and 91.7% correct detections and 97.1%, 98.0% and 96.0% correct detections for the bright targets. As expected, there was a main effect of luminance on detection rates, $F_{(2,18)} = 11.9$, $p < 0.001$. However, the

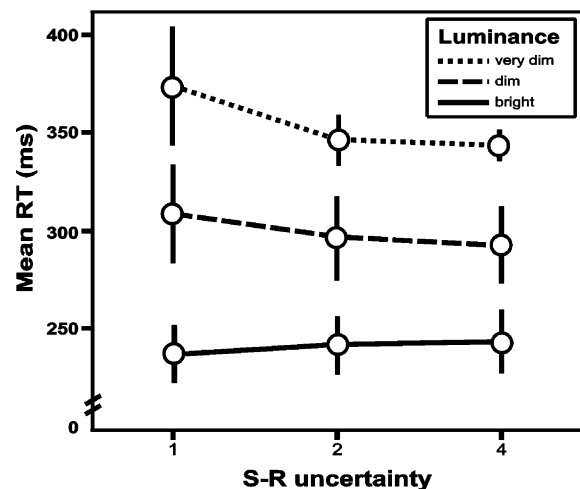


Fig. 2 Mean response latencies for all conditions. The error bars show the mean \pm SE

main effect of S-R uncertainty was not statistically significant, $F_{(2,18)} = 0.17$, $p > 0.84$. There was no interaction between luminance and S-R uncertainty, $F_{(4,18)} = 0.10$, $p > 0.98$.

We also analyzed saccade gain (endpoint accuracy), amplitude, and peak velocity as a function of target luminance and positional uncertainty. ANOVAs of saccade metrics revealed no significant effect of luminance ($p > 0.75$) or S-R uncertainty ($p > 0.60$) on saccade amplitude. Peak velocity was similarly unaffected by target luminance ($p > 0.99$) or S-R uncertainty ($p > 0.78$). Gain likewise showed no significant effect of luminance ($p > 0.85$) or S-R uncertainty ($p > 0.48$). There were no significant interactions between luminance and S-R uncertainty for any of these measures.

Discussion

We have shown here that the immunity to the effects of S-R uncertainty previously described for saccadic eye movements is maintained for targets ranging from suprathreshold intensities to those just above the detection threshold. Saccade latencies were substantially increased using near threshold targets, but that increase was equivalent across the three levels of S-R uncertainty. Detection rates also decreased with decreasing luminance, but neither target luminance nor S-R uncertainty significantly affected saccade amplitude, endpoint accuracy, or peak velocity in any of the conditions. It would appear that, once a peripheral target has been detected, the programming of motor parameters needed to fixate that target proceeds at a rate that is independent of the strength of the eliciting stimulus. In the context of models of the reaction time performance of the oculomotor system as a whole (Nozawa et al. 1994; Hughes et al. 1994), these results are consistent with a set of serially organized processing stages in which a target is detected, and once detected, the motor programs needed to fixate the target are activated and executed. From this perspective, we can conclude that detection precedes activation of the motor apparatus, and that the duration of post-detection processes that determine direction and amplitude is independent of the strength of the visual signals that initiated those events. It is especially noteworthy that, even at near-threshold luminances, there were no significant differences (in latency or accuracy) between saccades to targets drawn from a set of four

potential locations compared to those directed to a location that was known in advance. Just as in Kveraga et al. (2002), our subjects either did not prepare their saccade in advance (although they could when there was only one possible target location), or this preprogramming did not confer any advantage in the latency of their responses.

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