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Time course of visual extrapolation accuracy

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Abstract

In two experiments, we examined the extrapolation of a constant-velocity motion along a fixed circular path in the frontal plane. A target moved over an arc of 90 deg and then disappeared. Observers were to assume that the motion continued at the original velocity. After a variable time, a line appeared at another point on the circle to mark the end of the (invisible) 'motion'. Observers decided whether or not the target would have passed this end line, and gave a pass/no-pass response. In Experiment 1, a time course was established for the observed loss in accuracy with increasing duration of invisible motion. Two models of accuracy loss were constructed and tested. Both models assume that (1) extrapolation is performed by 'tracking' the position of the hidden target, and (2) there is no systematic velocity error in tracking, only random variation in tracker velocity. Both models predicted changes in hit and false alarm rates well, except in a condition where response asymmetries were present. In Experiment 2, the hypothesis that observers were tracking the hidden target was assessed by presenting a moving distractor during part of the trial. The presence of the distractor reduced performance under some conditions, suggesting that target tracking was occasionally disrupted. Grossly unequal distributions of pass/no-pass responses were observed for the fastest (8 deg/sec) and slowest (4 deg/sec) target velocities. However, the variable tracker models, using the parameter values from the first experiment, made accurate predictions for the 6 deg/sec condition, in which response distribution was nearly equal. Thus, there may be no need to posit systematic velocity error in motion tracking during extrapolation. The time course of accuracy decline can be accounted for by random variation in tracker velocity when response bias is absent.

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14. ABSTRACT

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1. Introduction

By the term 'visual extrapolation', we mean predicting the future position of an object moving relative to the observer. Visual extrapolation is used in virtually any kind of locomotion and in a wide variety of other situations. In this paper, we focus on the extrapolation of constant-velocity motion in the frontal plane. We determine how accuracy declines with the duration of extrapolation, and suggest possible explanations for this loss in accuracy.

Studies of extrapolation have used a variety of different paradigms, but they have several elements in common. Typically, a moving object (the *target*) is presented for some interval (the *visible segment*). This interval has an associated *visible time* and *visible distance*. The target then disappears (at the *disappearance point*), and observers estimate when it would pass an *endpoint* under the assumption that the characteristics of the initial motion continued while the object was invisible. We will call the interval during which the target is invisible the *hidden segment*, with an associated *hidden time* and *hidden distance*. *Hidden time* is also referred to as *extrapolation time*.

Extrapolation can be a demanding task. For example, it has been demonstrated that exponential functions are extremely difficult to estimate (e.g. Wagenaar and Timmers, 1979). Thus it may not be surprising that existing studies of the extrapolation of accelerated motion reveal a decline in extrapolation accuracy with hidden distance or time (e.g. Gottsdanker, 1952; Runeson, 1975; Jagacinski et al., 1983; Rosenbaum, 1975, Expt. 2). However, the results of studies of constant-velocity motion (e.g. Rosenbaum, 1975, Expt. 1; Slater-Hammel, 1955; Ellingstad, 1967; Wiener, 1962) do not always show such a decline.

Peterken et al. (1991) note that methodological problems obscure the interpretation of the results of many motion extrapolation studies. In their own experiments, Peterken et al. (1991) used a paradigm in which a small target moves left to right across a CRT for some visible distance, then becomes invisible. Observers estimated (by pressing a key) the time that the dot would have arrived at an endpoint marker placed various distances away from the disappearance point. Peterken et al. concluded that the best predictor of absolute extrapolation error was neither the visible distance nor the hidden distance. Rather, error was most strongly related to hidden time. Thus, when extrapolating a motion, the longer the time over which the extrapolation must be extended, the more error there is likely to be, regardless of the distance over which the target moves. As Peterken et al. put it, "temporal, rather than spatial, factors are responsible for differences in estimation performance" (p. 10). They also note that "substantial error does not occur until about a second has elapsed since the last input of information" (p. 14). This latter point may explain the conclusion of Rosenbaum (1975) that extrapolation of constant-velocity motion is performed accurately, since the longest hidden time Rosenbaum used was 1 sec. Long hidden times are seldom used in studies of extrapolation; indeed the longest time used by Peterken et al. was just over 3 seconds. Here (Experiment 2), we obtain data for hidden times of up to 7 seconds.

To summarize: there is evidence that, even for constant-velocity motion, extrapolation accuracy declines with the length of time that the observer must keep track of the target after it has disappeared. However, this decline is not always obtained, perhaps because hidden times are typically short. If extrapolation accuracy does decline with time, then it is of interest to examine the time course of this decline to see what it may tell us about the visual/cognitive mechanisms that are used in extrapolation. In the experiments below, we obtain a time course for extrapolation accuracy under various conditions, and propose a simple model for extrapolation accuracy over time.

2. Experiment 1

It is possible to postulate a visual extrapolation process in which accuracy does not decline with hidden time. Suppose, for example, that extrapolation is performed by (1) tracking the target while it is visible, and then (2) continuing to track the target location after the disappearance point. If a tracking mechanism (perhaps an attentional 'spotlight') were to track the visible target accurately and continue to track at the same rate after the target disappeared, then error should be very low for all hidden times, as long as tracking was not interrupted. But the Peterken et al. (1991) results show that both the size and the variability of extrapolation error increase considerably with hidden time.

There are several plausible explanations for this result. Again, consider an attentional tracking mechanism as an example. Tracking error would increase with time if the tracking mechanism: (1) tracked with a different velocity on each trial, even though the average velocity was correct; (2) tracked with the correct average velocity, but was unsteady during the course of a trial; (3) accelerated or decelerated steadily; or (4) maintained a steady velocity, but one which was higher or lower than the target velocity.

Explanations 3 and 4 incorporate the assumption that the tracking mechanism is subject to *systematic* error, either in velocity or acceleration or both. Before accepting the decline in extrapolation accuracy as proof of this assumption, one must determine if the data can be explained without it. Explanations 1 and 2 are simpler in the sense that no systematic error is assumed. We therefore decided to construct models embodying the assumptions of explanations 1 and 2 in order to see if the time course of extrapolation accuracy could be predicted without assuming systematic tracking error.

In generating these models, we assumed that average tracking velocity always matched that of the target. For explanation 1, which we call the "steady but errorful tracker" model, the velocity of the tracker was assumed to be constant throughout a trial, but was selected anew for each trial from a normal distribution with a mean of the target velocity. For explanation 2, which we call the "unsteady tracker" model, the extrapolation interval was subdivided, and for each subinterval a velocity was selected independently, again from a normal distribution with a mean of the target velocity. Predictions from each of these models are derived in the Appendix.[1] The models differ in the predicted rate of change in extrapolation performance over time; performance changes faster for the steady tracker model than for the unsteady tracker model.

Thus, the time course of extrapolation performance may be useful for distinguishing between models of extrapolation. Time course data could help us decide whether variability in a hypothetical tracking mechanism is enough to explain the drop in accuracy; whether one needs to add constant velocity error or systematic acceleration/deceleration to a model of the tracker; or whether some non-tracking model of extrapolation (e.g. counting or timing) is more useful.

A critical question concerns how best to obtain data on the time course of extrapolation performance, especially in the context of hypotheses about possible mechanisms that extrapolate via tracking of the target. The results of several of our pilot experiments suggested that if the measurement paradigm permits the use of a simple timing or counting strategy, observers will use this strategy instead of attempting to track the target during the hidden interval. Therefore, in the present studies, the endpoint is varied from trial to trial and is *not displayed* until the end of the trial. Thus, the observer does not know during the visible segment what proportion of the entire path (and thus, what proportion of the total time) the target will be hidden. Another finding from pilot studies was that requiring observers to produce a temporal interval (e.g. by pressing a key when the target reaches the endpoint) is likely to introduce a sizable but irrelevant source of variability -namely, variability in the time to initiate the movement that results in a keypress that is precisely coordinated with the target arrival time. Therefore we asked observers to make a judgment; to decide whether the target would have progressed past the location at which the endpoint is presented, or whether it would have failed to reach the endpoint.

Finally, we wanted to use a relatively large range of hidden times in order to examine as much of the time/accuracy function as possible. In order to do this, we abandoned the linear motion used in pilot studies and in most prior studies of extrapolation. Instead, the target moved around the circumference of a circle.

2.1. Method

Observers

Six observers (three men, three women) with normal or corrected-to-normal vision were paid for their participation. Three of the observers were also in Experiment 2, which was run during the same time period.

Apparatus

Stimuli were displayed on a NEC Multisync XL monitor driven by a Silicon Graphics Irisvision 24-bit graphics card operating with a resolution of 1024 (horizontal) × 768 (vertical) pixels and controlled by an 80386-based computer. Stimuli were viewed from a distance of 60 cm in an otherwise dark room.

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[1] This derivation was suggested by Dirk Vorberg.

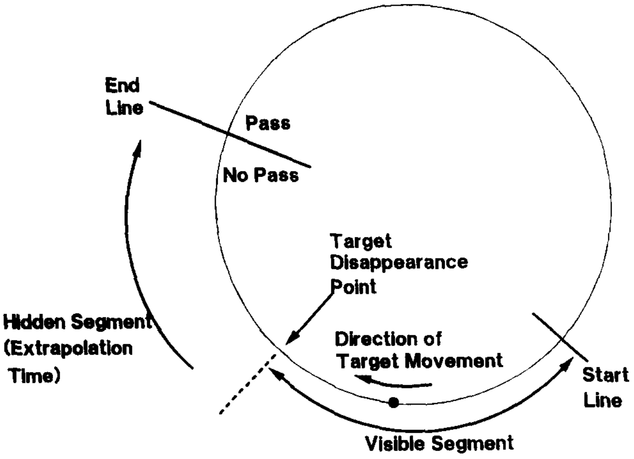

Fig. 1. Illustration of the procedure used to elicit extrapolation in Experiment 1.

Procedure

Fig. 1 illustrates the procedure used to elicit extrapolations. First, a fixation point, a faint circle with a radius of 9 deg, and a start line 1 deg in length perpendicular to the circle were presented for 1 sec. Then a target began to move either clockwise or counterclockwise at one of three 'velocities' (4, 6 or 8 deg/sec). The term velocity here actually refers to a scalar value, the speed in degrees/sec of visual angle along the circular path. Target movement continued at a constant speed on a circular path, covering an arc of 90 deg. The target then disappeared. The observer was instructed to assume that the invisible target was continuing to move at the observed velocity. After a variable period of time, a 2-deg-long end line perpendicular to the path was displayed until the observer responded. The observer was instructed to decide whether or not the invisible target would have passed the end line by the time the line was displayed. The observer's response ("pass" or "no-pass") was indicated by pressing one of two keys on a standard keyboard. An incorrect response was signaled by a brief tone.

On each trial, the end line was presented at one of six arc angles beyond the disappearance point in the direction of motion. The angles used varied with velocity. The end line for the 4 deg/sec target was either 20, 40, 60, 80, 100, or 120 arc degrees beyond the 90 deg disappearance point, so that the maximum total arc distance was 210 deg. End lines for the 6 deg/sec target were 30, 60, 90, 120, 150, or 180 deg beyond the disappearance point, and the corresponding end line positions for the 8 deg/sec target were 40, 80, 120, 160, 200, or 240 deg. These end line positions were chosen so that each of the three velocities would result in the same set of six extrapolation times. The data are analyzed in terms of these times, which range from 784 to 4717 msec.

Pass/no-pass trials were generated by varying the time at which the end line was displayed. For example, on each trial for a given target velocity, one of the six possible end line positions was chosen at random. The program then computed the time at which the (invisible) target would have arrived at this end line position. If the trial was to be a pass trial, then the end line was presented 300 msec after the target arrival time. If it was a no-pass trail, the end line was presented 300 msec before target arrival. Pass/no-pass trials were selected at random and were equally likely. We had a choice of keeping either gate offset distance or gate offset time constant for motions of different velocities. Because Peterken et al. (1991) and the results of our own pilot studies indicated that time was the major determinant of accuracy, we elected to keep gate offset time constant.

The experiment consisted of 36 blocks of 100 trials each, with 3 blocks presented during each of 12 45-min sessions. At the end of each block, the number of errors made during the block was displayed. Observers were instructed to try to minimize this number. All trials within a session used the same target velocity. Order of presentation of target velocity sessions was counterbalanced, with each observer receiving a different order.

Data analysis

Mean proportion correct for each combination of target velocity and extrapolation time were obtained from each of the 36 blocks from each observer. An analysis of variance (ANOVA) was conducted on these proportions, with velocity, extrapolation time, and observers as the factors and blocks as the replications. Separate ANOVAS on data from each observer were also conducted. The same analyses were performed for the block mean proportions of pass responses. For purposes of modeling, two other proportions, *p*('pass'|pass trial), and *p*('pass'| no-pass trial) were also computed for each velocity and extrapolation time.

2.2. Results

Proportion of correct responses as a function of extrapolation time, with target velocity as a parameter, are shown as the solid lines in Fig. 2. The figure shows that slightly higher accuracy was achieved with the faster targets ($F(2,1295) = 7.59$, $p < 0.001$). However, only two of the six observers showed velocity effects that

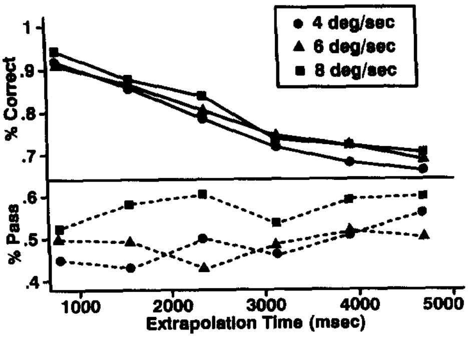

Fig. 2. Proportion of correct responses (solid lines) and proportion of pass responses (dotted lines) as a function of extrapolation time, with target velocity as a parameter (Experiment 1).

approached significance. Targets of all velocities showed a significant decline in accuracy with extrapolation time ($F(5,1295) = 153.6$, $p < 0.001$). This decline occurred in all six individual observers ($p < 0.001$ for every observer). The velocity × extrapolation time interaction did not approach significance, suggesting that whatever causes the observed decline in accuracy is operating at all of the velocities used in the experiment.

The dotted lines in Fig. 2 are the proportion of "pass" responses, again with target velocity as a parameter. Higher-velocity targets were significantly more likely than lower-velocity targets to elicit a pass response ($F(2,1295) = 46.2$, $p < 0.001$). The overall proportion of pass responses increased significantly with extrapolation time ($F(5,1295) = 6.35$, $p < 0.001$). However, only in the case of the 8 deg/sec targets did this increase result in an increase in deviation from 50%. Thus, the observed decline in extrapolation accuracy over time at all velocities cannot be explained by a change in the probability of choosing either a pass or a no-pass response.

2.3. *Discussion*

The results of Experiment 1 establish that (1) extrapolation accuracy declines with time; (2) the rate of decline is about the same for targets of different velocity (if the temporal window for defining a correct extrapolation is held constant); and (3) the decline in accuracy cannot be due to asymmetric response preference. In addition, the experiment yields a time course for extrapolation accuracy. We now turn to an analysis of this time course with respect to possible models of extrapolation error.

Two potential models have been discussed already: the "steady but errorful tracker", and the "unsteady tracker". Predictions for these two models were generated for the proportions p('pass'|pass trial), and p('pass'| no-pass trial), which correspond respectively to hits and false alarms if the pass trial is defined as the signal. Each model has a single parameter, the value of which changes with target velocity. For the steady tracker model, this parameter is the standard deviation s_1 of the tracker velocity distribution over trials. For the unsteady tracker model, the parameter s_2 represents the overall standard deviation of the tracker velocity. This variation arises from changes in tracker velocity during each subinterval of extrapolation time within a trial. In order to test the simplest version of each model, both s_1 and s_2 were set to be a constant multiple of target velocity, so that each model required only one free parameter to generate predictions for all 18 combinations of extrapolation time and velocity. Approximate best-fitting versions of these models are plotted as solid lines in Fig. 3, Fig. 4 and Fig. 5. The points plotted in these figures are the observed proportions of hits (top panels) and false alarms (bottom panels) from Experiment 1. The values of the standard-deviation to velocity-ratio parameter (0.15 for steady tracker and 7.5 for unsteady tracker) were chosen so that mean accuracy for the two models would be approximately equal, thus highlighting differences in the shapes of the predicted performance curves. It is clear even from this approximate method that both models can

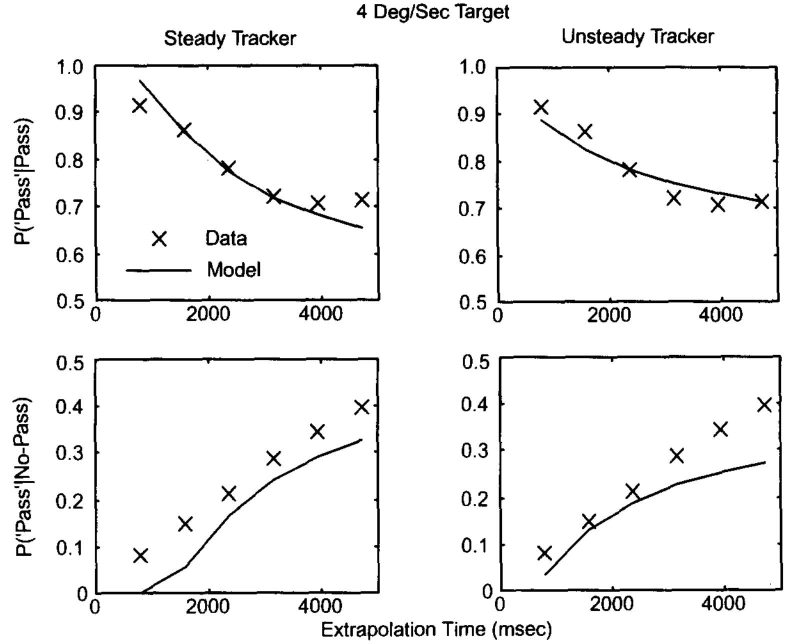

Fig. 3. Predictions (solid lines) of two models that assume only random variation in the velocity of a motion tracking mechanism, compared with data (plotted points) from the 4 deg/sec target condition, Experiment 1. Left panels contain hit rate and false alarm rate predictions from a "steady tracker" model with only trial-to-trial velocity variation; right panels show predictions of an "unsteady tracker" model in which tracker velocity varies within a trial.

account reasonably well for the decline in hit rate with extrapolation time for the smallest two velocities.

The results of this analysis suggest that either of these simple, one-parameter models based on tracker variability may be adequate to account for the decline in extrapolation accuracy with time; there may be no need to postulate any *systematic* extrapolation error. However, the fit of the models is by no means perfect. For example, for the 8 deg/sec target, observers produced both more hits and slightly more false alarms than either model predicts. This is consistent with the relatively high proportion of "pass" responses observed in this case, and suggests that the models would have to incorporate a response bias to account perfectly for the 8 deg/sec data. Also, when performance was examined by observer, two observers, CS and MS, showed an unusually slow decline in accuracy with time. One of these (CS) reported using a strategy which involved counting the time interval during which the target was presented and then trying to update his target tracking during the hidden segment with a continuing count. Although the paradigm used here was designed to make pure timing strategies difficult to use (because the endpoint is not known in advance), a hybrid strategy that maintains tracking but also relies on some either implicit or explicit representation of elapsed time could have been used by some observers.

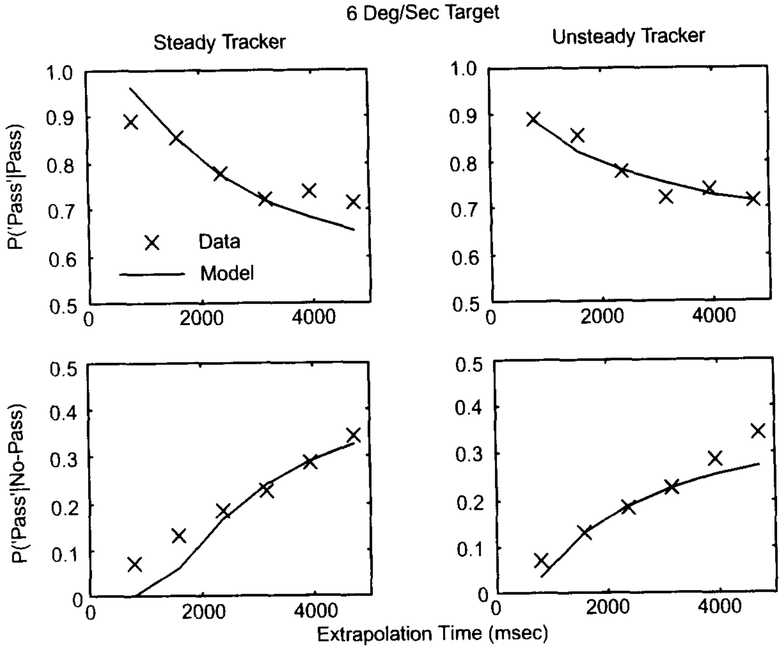

Fig. 4. Predictions of the steady tracker and unsteady tracker models for a 6 deg/sec target, and the corresponding data from Experiment 1.

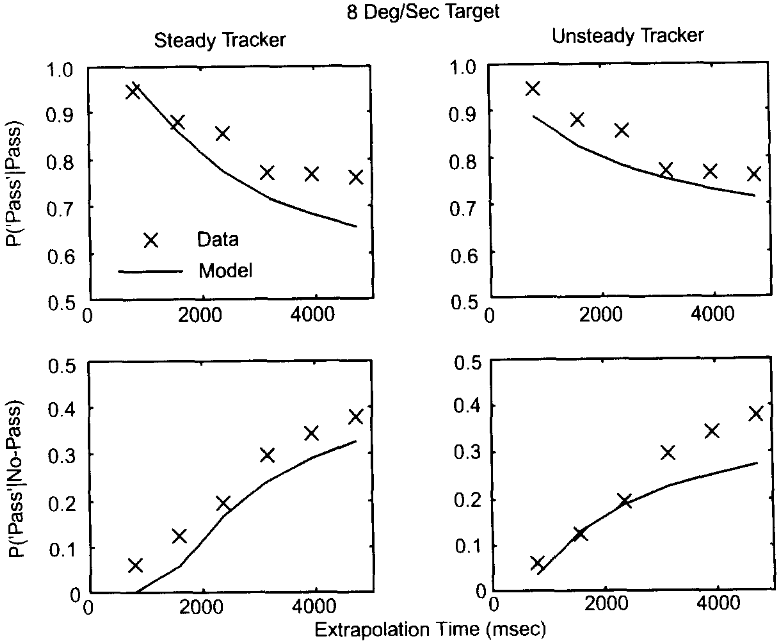

Fig. 5. Predictions of the steady tracker and unsteady tracker models for an 8 deg/sec target, and the corresponding data from Experiment 1.

One aspect of the design of this experiment may have contributed to the potential utility of timing or counting strategies. The velocity of the target was the same for all trials within a session. This may have allowed some observers to learn to base their extrapolations at least partially on the constant duration of the visible segment. In the next experiment, target velocities were selected at random from trial to trial. In addition, a distractor is introduced that should produce some disruption of tracking if observers really are attempting to track the target.

3. Experiment 2

As the preceding discussion implies, it is possible to distinguish two different classes of hypotheses about the mechanisms that underlie the ability to extrapolate motion. We will refer to these as "tracking" hypotheses and "timing" hypotheses. The primary distinction between them is that tracking hypotheses postulate mechanisms that follow the motion of the target during the hidden interval, whereas timing hypotheses require no such mechanism.

One possible tracking mechanism might be to try to match the movement of the eyes to the initial target motion, and then continue this eye movement until the endpoint is reached. The time required to move the eyes would be an estimate of the time required for the target to move. It has been noted in many studies of extrapolation that observers tend to follow the imaginary motion with their eyes. However, this does not mean that the observer's predictions about the position of the object are based on these eye movements. It could be that the cognitive systems used to make such predictions do not have access to eye position or eye movement time. Moreover, Peterken et al. (1991) showed that extrapolations are as accurate when observers maintain fixation as when they move their eyes. This argues strongly against the eye-following hypothesis. Although it may be possible to find conditions under which extrapolations made with eye movements are slightly better than those made without, the Peterken et al. results indicate that observers can predict constant-velocity frontal-plane motion quite well without moving their eyes if they have to.

Another possible tracking hypothesis is based on covert movements of focal attention (e.g. Posner, 1980). It is possible that observers follow visual motions with an attentional "spotlight", and that they can continue to move this spotlight across the visual field after the disappearance of the moving object. When the spotlight reaches the endpoint, they make their response. This explanation, however, assumes a particular and somewhat controversial view of the nature of focal attention, namely, that attention operates like a spotlight that can move across the visual field in a way that matches the motion of a visible object, and continue such motion after the object disappears. Some researchers (e.g. Shulman et al., 1979; Tsal, 1983) have presented results compatible with this view of attention. Others (e.g. Eriksen and Murphy, 1987; Cheal and Lyon, 1989) have argued against it. However, even discussions supporting a moving spotlight view assume that the spotlight moves at a constant velocity. The possibility that an attentional spotlight might be accelerated or decelerated to match the motion of an object has not, to our knowledge, been considered seriously. Nor has the possibility that the spotlight could continue to accelerate after the disappearance of the object. Thus, the fact that observers can sometimes produce reasonably accurate extrapolations of accelerated motion may suggest either that (1) the attentional spotlight is very flexible in its range of motions; (2) accurate extrapolations of accelerated motion can be produced by constant-velocity attentional movements; or (3) spotlight movements are not the primary mechanism by which extrapolations are performed.

The second general class of hypotheses, timing hypotheses, do not require a motion tracking mechanism, but they do require some method of computing elapsed time, and some way to integrate velocity and distance information. It is assumed that, for purposes of extrapolation, observers view visual motion as a temporal event, or sequence of events. According to this hypothesis, the visible portion of the motion is clocked by a central timing mechanism. Mental counting is one possibility for such a timing mechanism, but less conscious mechanisms may be more likely. In any case, this "elapsed time" is used as the basis for the time the observer waits before responding.

Some extrapolation conditions could make it easier to use such timing strategies. An important factor is the predictability of an extrapolation trial. For example, if hidden distance is held constant, observers may learn to compare visible distance to hidden distance, and then use visible time to compute an estimate of hidden time without the need to continuously follow the object motion. Further, even when hidden distance is varied, if observers know where the endpoint is as the trial starts, they may not need to try to follow the motion during the hidden segment, but rather may learn to use a variation of the temporal reproduction strategy. In the extrapolation task used here, the endpoint is not presented until the end of the trial, thus making it unlikely that observers can perform the task well using only information about time intervals.

Therefore we suggest that extrapolation in this task reflects, at least in part, the operation of a motion tracking mechanism. This idea was tested in Experiment 2, in which we attempted to disrupt tracking by presenting a moving distractor during the hidden segment. If the presence of a moving distractor degrades extrapolation accuracy, then some kind of tracking mechanism may be a component of visual extrapolation under these conditions, either as the primary basis for extrapolation or as an adjunct to a timing mechanism. It will then be possible to see if characteristics of this tracking mechanism can account for the time course of extrapolation accuracy.

3.1. Method

Observers

Four observers with normal or corrected-to-normal vision were paid for participation. Three of these were participants in Experiment 1.

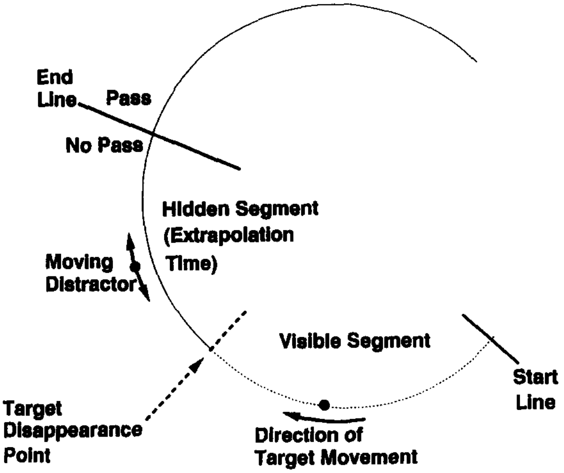

Fig. 6. Extrapolation task for Experiment 2, in which a moving distractor was displayed during the hidden segment.

Stimuli

Stimuli were presented on the same apparatus as in Experiment 1. The display, shown in Fig. 6, was the same as that of Experiment 1 except that (1) the target path guide was a semicircle instead of a full circle, and (2) on some trials, a blue, moving distractor dot was presented. This distractor appeared when the target disappeared. The initial position of the distractor was at one of two positions along the circular target path: (1) the target disappearance point (the "near position"), or (2) a position 180 deg further along the path from the disappearance point (the "far position"). If the distractor appeared in the near position, then it always moved in the direction of the target (congruent distractor). If it appeared in the far position, then it always moved in a direction opposite to the target motion (incongruent distractor). In either case, the distractor continued to move while the observer was attempting to extrapolate the target motion, and it disappeared when it had traversed an arc of 180 degrees, or when the endpoint was displayed, whichever came first. The distractor followed an arc from a circular path having a radius that was offset from the target path radius by one of five values (plus or minus 0.33 1, or 2 deg). It moved at one of two randomly selected constant speeds (1 or 5 deg/sec). A distractor was present on 67% of the trials. The four distractor movement conditions (2 speeds, 2 directions) were equiprobable, so each occurred on 16.7% of the trials.

Procedure

The procedure was the same as in Experiment 1, except that (1) observers were informed about the existence of a distractor on some trials, and were instructed to try to ignore it; (2) target velocity was randomized within a session instead of being blocked by session, and observers were so informed (there were 16 300-trial

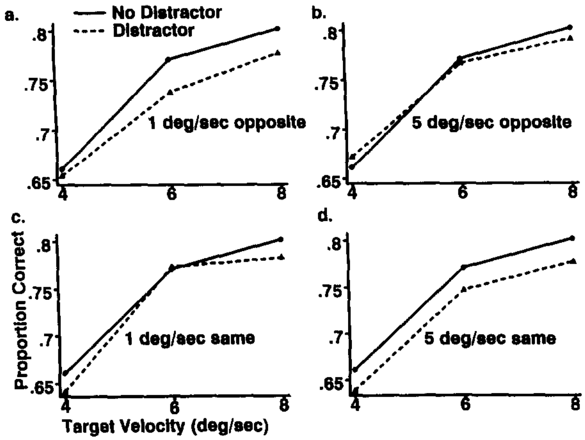

Fig. 7. Extrapolation accuracy when a moving distractor is present (Experiment 2), plotted as a function of target velocity. Each of the four panels shows data from a particular distractor speed and direction (dotted line) with the data for the no-distractor condition (solid lines).

sessions per observer), and (3) the set of possible end-line positions did not vary with velocity. End line positions in degrees from the disappearance point were: 30, 60, 90, 120, 150 and 180 deg.

Data analysis

Mean proportion correct and proportion of pass responses for each session of each observer were obtained for each combination of velocity, endpoint position, and distractor presence/movement. (A preliminary analysis of distractor offset showed no effects on performance, so this variable was not considered further). Four ANOVAs were conducted on each of these dependent variables, one for each of the four distractor movement conditions. Each ANOVA included the following factors: distractor presence/absence, velocity, endpoint position, and observer. In tests of model predictions, proportions of 'pass'|pass and 'pass'|no-pass trials were computed as in Experiment 1.

3.2. Results

Panels a–d of Fig. 7 show the effects of the four distractor-present conditions on extrapolation accuracy. A plot of data from the no-distractor condition is repeated in each panel in order to facilitate visual comparison with the distractor-present conditions. As is evident in the figure, some distractor conditions degrade accuracy and some do not. A distractor moving quickly in the direction of the target (panel d) significantly reduces accuracy ($F(1,2121) = 5.29$, $p < 0.022$). A distractor moving slowly in the opposite direction of the target (panel a) may also reduce accuracy, though the effect is not quite significant ($F(1,2126) = 3.79$, $p < 0.052$). The effects of a distractor do not approach significance in either of the other two conditions.

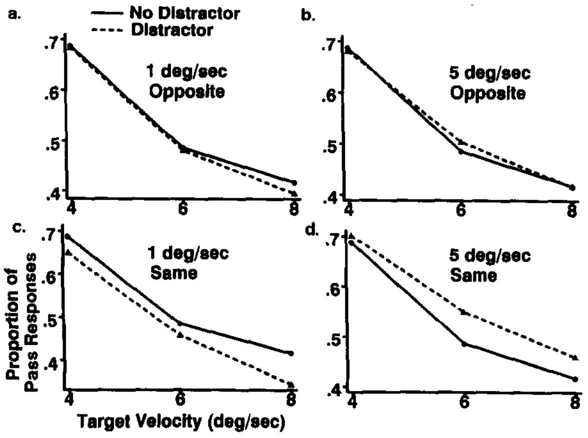

Fig. 8. Proportion of pass responses as a function of target velocity for different directions and velocities of a moving distractor (Experiment 2).

Effects of distractor presence and congruence on the proportion of pass responses are shown in panels a–d of Fig. 8. As in Fig. 8, data from the no-distractor condition are repeated in each panel. It is evident that a distractor affects the proportion of pass responses only when it travels in the same direction as the target (panels c and d), although the effects of slow and fast distractors are different. Both effects are significant: 1 deg/sec distractor ($F(1,2126) = 14.9$, $p < 0.0001$); 5 deg/sec distractor ($F(1,2121) = 10.9$, $p < 0.001$).

In addition to the effects of distractor presence and congruence, there were large effects of the velocity of the target and the placement of the endpoint. For all distractor conditions, accuracy was greater for faster velocities and nearer endpoint locations (all p's < 0.00001), and there were no significant velocity x endpoint-location interactions. Fig. 9 shows the data collapsed over distractor position plotted as a function of extrapolation time. As was the case in Experiment 1, there

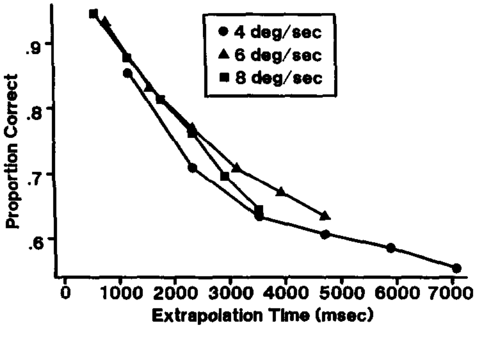

Fig. 9. Proportion of correct responses as a function of extrapolation time, with target velocity as a parameter (Experiment 2).

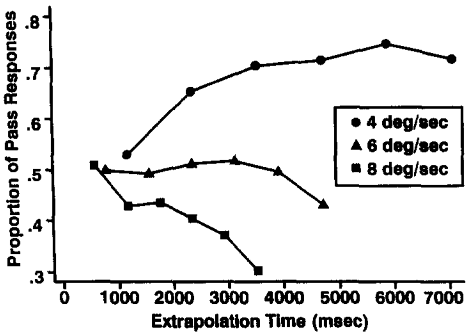

Fig. 10. Proportion of pass responses as a function of extrapolation time, with target velocity as a parameter (Experiment 2).

is a marked decline in performance with increasing extrapolation time for targets of all three velocities.

Fig. 10 shows the corresponding plots for the proportion of pass responses. Again, there were effects of velocity and endpoint location for all distractor conditions (all p's < 0.03). However, the velocity effects were much larger than in Experiment 1, and, surprisingly, they were in the opposite direction. In Experiment 1, the fastest targets had the largest proportion of pass responses, whereas in Experiment 2, the slowest targets were more far more likely to elicit a pass response. There were also large and consistent velocity-by-endpoint-location interactions (all p's < 0.00001). For all distractor conditions, the proportion of pass responses increased with time for the slowest (4 deg/sec) targets, and decreased with time for the fastest (8 deg/sec).

3.3. Discussion

The results of Experiment 2 show that extrapolation performance can be degraded by the presence of a single irrelevant moving stimulus presented during the hidden interval. This suggests that visual extrapolation under the present conditions makes use of some kind of tracking mechanism that can be disrupted by irrelevant moving stimuli.

There are, however, some potential alternative interpretations of the results. One is that observers sometimes mistook the distractor for a continuation of the target motion. This is unlikely because (1) distractor and target are different colors; (2) the distractor path is displaced from the extrapolated target path, even when they travel the same direction; (3) the distractor never travels at the same speed as the target; and (4) distractor starting position is at least 90 deg away from target starting position, which is presented in advance. Another possibility is that the presence of the distractor disrupted observers' perception of the target motion itself, rather than their extrapolation of it. This is unlikely because the distractor

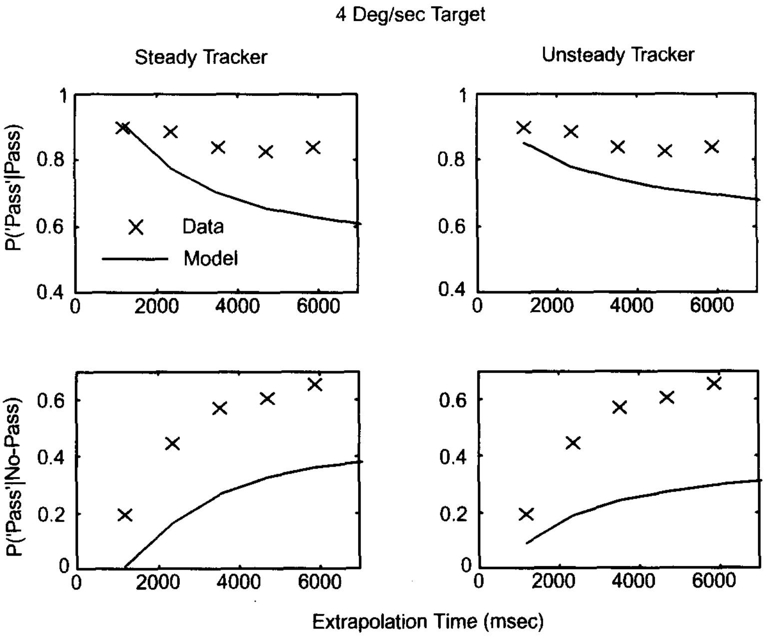

Fig. 11. Solid lines are predicted hit and false alarm rates of a steady tracker model (left panels) and an unsteady tracker model (right panels) for a 4 deg/sec target velocity; plotted points are the corresponding data from Experiment 2.

was presented only after the target motion was complete and the target had disappeared.

Finally, there is the possibility that observers are not using a tracking mechanism, but rather some sort of timing mechanism that is itself sensitive to the presence of a visual distractor. For example, the presence of a fast distractor could speed up the time base; a slow distractor could slow it down. However, by itself, this explanation would not predict differences in distractor effects due to the direction of the distractor. Moreover, when asked how they were trying to perform the task, none of these observers described a timing strategy. They all claimed to be trying to follow the position of the invisible target until the endpoint appeared.

Thus, although it is difficult to completely rule out alternative explanations, the effects of the moving distractor suggest that some kind of tracking underlies the ability to perform visual extrapolation in this experiment. We now return to the issue addressed in Experiment 1: can a variable tracker account for the decline in extrapolation performance with time? Fig. 11, Fig. 12 and Fig. 13 show the predictions of the two tracking variability models discussed in Experiment 1 for the three target velocities, averaged over distractor conditions. The predicted hit rates and false-alarm rates for the steady tracker model are shown as solid lines on the left-hand panels; predictions of the unsteady tracker model are on the right. As in Experiment 1, we used only a single parameter (ratio of tracker velocity variation

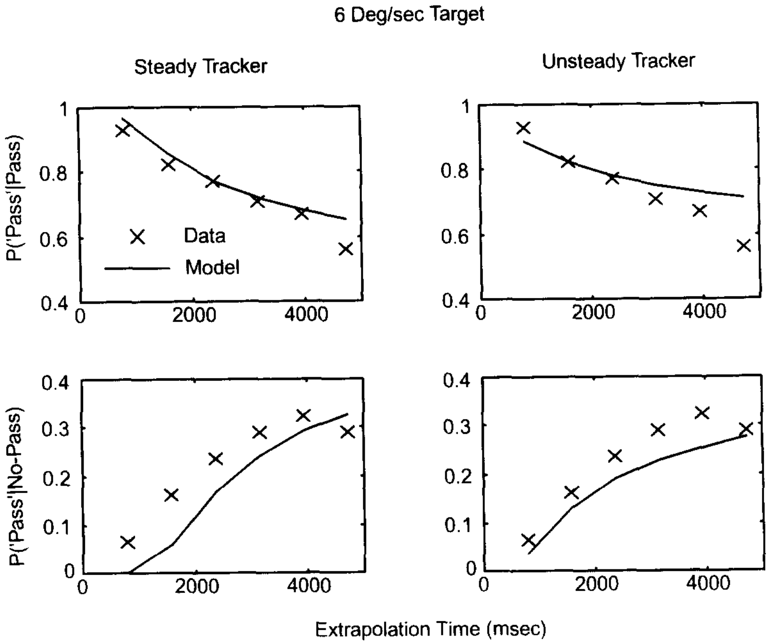

Fig. 12. Predictions of the steady tracker and unsteady tracker models for a 6 deg/sec target, and the corresponding data from Experiment 2.

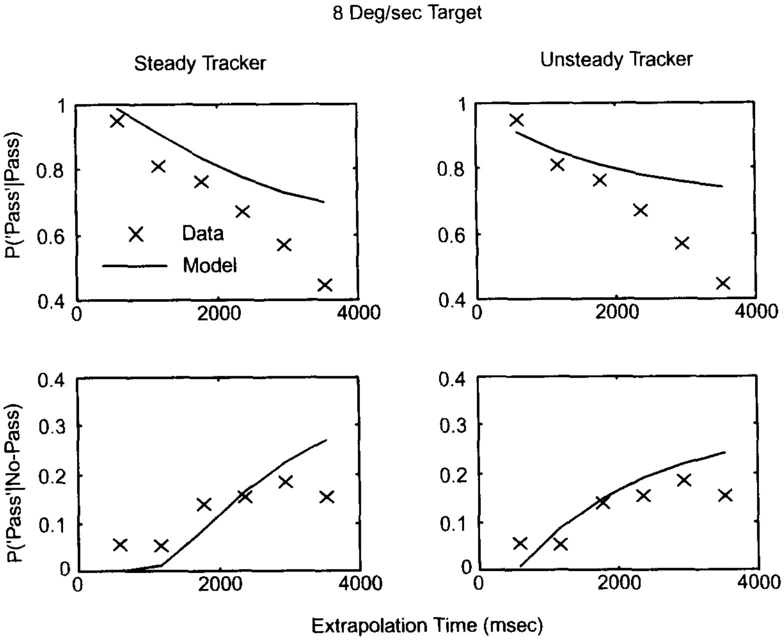

Fig. 13. Predictions of the steady tracker and unsteady tracker models for an 8 deg/sec target, and the corresponding data from Experiment 2.

to target velocity) to account for all three target velocity conditions. Moreover, the value of this parameter was constrained to be the same as that used in Experiment 1, so that the predictions for Experiment 2 used no free parameters.

As is shown in Fig. 11 and Fig. 13, both models fail this stringent test for the slowest and fastest targets. However, the steady tracker model does reasonably well in predicting hit rates for the 6 deg/sec targets (Fig. 12). These results are consistent with the data on proportion of pass responses shown in Fig. 10. The 4 deg/sec and 8 deg/sec targets elicited a large preponderance of either pass or no-pass responses, whereas the 6 deg/sec targets did not. (We discuss below the possibility that these response frequency effects may be largely a consequence of the mixture of target velocities within a block in this experiment.) In the 4 deg/sec case, proportion of pass responses was high, which should result in more hits and more false-alarms than the model predicts. This result is evident in Fig. 11. In the 8 deg/sec case, proportion of pass responses was low, therefore observed hits and false-alarms should be low relative to the model predictions, and they were (Fig. 13). Finally, the much better fit of the models in the 6 deg/sec case suggests that, when response frequencies are approximately equal, tracker variability alone may account for the bulk of extrapolation error over time.

4. General discussion

An important characteristic of visual extrapolation performance, reported by Peterken et al. (1991) and examined in detail here, is that accuracy declines markedly over time, even when the velocity of the target is constant. We have shown that the rate of decline does not change substantially with velocity under the conditions of the present experiments; that the decline cannot be solely due to response frequency effects; and the presence of a moving distractor can disrupt accuracy. The latter finding suggests that some kind of target tracking process is at least a component of extrapolation performance.

There are several possible hypotheses about the tracking process that are compatible with a decline in accuracy with time. Predictions from two such hypotheses were derived and tested against the accuracy time course obtained in Experiments 1 and 2. Both hypotheses assert that there is random variation in tracker velocity (from trial to trial or within a trial) about a mean equal to the target velocity. The predictions of both hypotheses were reasonably accurate for conditions in which there was no large preponderance of pass or no-pass responses.

Despite the (qualified) success of simple random-error models in these experiments, there are other possible explanations for the decline in extrapolation accuracy with time. These assume systematic, rather than random, deviations from the target velocity. There are two kinds of systematic deviations to consider: (1) a constant difference between tracking velocity and target velocity, and (2) deceleration or acceleration of tracking. Let us examine the constant velocity difference hypothesis first. It is clear that the consequences of a constant velocity error grow with time. For example, the shortest trials for the 8 deg/sec condition in Experiment 2 have a hidden segment time of only 594 msec. For such short trials, the endpoint placement deviation (300 msec) is almost half of the hidden segment time. Thus, even if the tracking velocity on a given trial were only 70% of the target velocity, the tracking time would be within the 300 msec deviation, and the proportion of correct trials should be high (95% of these trials were responded to correctly in Experiment 2). For more distant endpoint placements, the tracking velocity needs to be considerably more accurate in order for a response to be correct. Therefore, if there is no acceleration or deceleration in tracking, a given velocity difference between the target and the tracking process will result in a decline in the proportion of correct responses with time.

Another possibility that also could result in a drop in accuracy with time is the acceleration or deceleration of tracking during the hidden segment. As was shown in Fig. 10 (Experiment 2), the proportion of pass responses increases markedly with time for the 4 deg/sec targets, decreases markedly for the 8 deg/sec targets, and remains about the same for the 6 deg/sec targets. An increase or decrease in proportion of pass responses could be produced by a change in the speed of the tracking process. If tracking slows down with time, then the proportion of pass responses should drop; if tracking speeds up, this proportion should rise. Either speedup or slowdown of tracking could reduce accuracy (*if* the initial velocity of the tracking process is accurate). If this speedup or slowdown were a major contributor to the overall decline in accuracy with time, however, then accuracy for the 8 and 4 deg/sec targets should have declined much more than the 6 deg/sec target. Examination of Fig. 9 shows little confirmation of this prediction. Accuracy for the 6 deg/sec target is indeed somewhat higher than for the 4 deg/sec target, and it may be even slightly higher than the 8 deg target for the larger hidden times. But the decline in accuracy with time is about the same for all three velocities, and this decline is much larger than even the largest difference between velocity curves.

What accounts for the velocity-dependent change in the proportion of pass responses over time? Why were effects so striking in Experiment 2 and not in Experiment 1? Perhaps these effects result from the random mixture of target velocities within a block in Experiment 2. It is possible that the tracking mechanism tends to be influenced by the speed of targets in previous trials. Table 1

Table 1
Proportion of pass responses by current trial velocity and previous trial velocity, Experiment 2.

	Velocity on current trial		
	4 deg/sec	6 deg/sec	8 deg/sec
Velocity on previous trial			
4 deg/sec	0.62	0.43	0.38
6 deg/sec	0.69	0.5	0.41
8 deg/sec	0.72	0.55	0.44

shows the proportion of pass responses in Experiment 2 crosstabulated by the velocity of the current trial and the immediately preceding trial. As the table shows, observers are more likely to respond "pass" for the slow target when the previous target had been faster, and vice versa.

What could be causing this apparent hysteresis effect? Perhaps observers begin tracking at the correct speed while the target is visible. After the target disappears, however, there may be a tendency to slow down or speed up toward the velocity that the tracker used on the previous trial. Another possible explanation is that there may be a tendency to track at the median velocity of all the presented trials, so that the tracking of slow targets tends to gradually accelerate, the tracking of fast targets tends to decelerate, and the tracking of medium speed targets shows little speed change. However, as noted earlier, these changes seem to have little effect on the loss of accuracy with extrapolation time.

5. Conclusion

We have shown that, under some conditions, the presence of a moving distractor reduces extrapolation accuracy. This suggests that observers are using some mechanism (perhaps covert shifts of attention) to track the position of the target object after it disappears. The results also suggest that very simple, one-parameter models based on random deviations in tracker velocity can account for the time course of extrapolation accuracy when response bias is not a factor. This is not to say that another model combining random error with systematic tracker velocity error could not also account for the data, but such a model would involve more than a single parameter. Thus, there is no need to invoke nonrandom velocity error in the tracking process when the velocity of the motion is constant.

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We thank Dr. Gerard P. van Galen, Dr. Dirk Vorberg and an anonymous reviewer for their helpful comments on an earlier draft, and Tim Askins for programming assistance. This research was funded by the U.S. Air Force Office of Scientific Research Life Sciences Task 2313T3 and by the U.S. Air Force Human Resources Laboratory Contract F33615-87-C-0012.

Appendix A

Derivation of predictions for steady-tracker and unsteady-tracker models

The objective is to derive predictions for two quantities as a function of velocity v and extrapolation time t: (1) the probability of a 'pass' response on a pass trial,

p('pass'|pass), and (2) the probability of a 'pass' response on a no-pass trail, p('pass'|no-pass). This is accomplished by considering the predicted distribution of extrapolated position $p(v,t)$ under the assumptions of each model.

Model 1 (steady tracker): According to this model, the velocity distribution V of the tracker is normal with a mean of v and standard deviation s_1. The expected mean and variance of extrapolated position given this model is:

$$E[p(v,t)] = E[Vt] = E[V]t = vt,$$

$$\operatorname{var}[p(v,t)] = \operatorname{var}[Vt] = \operatorname{var}[V]t^2 = s_1^2 t^2.$$

In order for the observer to respond 'pass' on a pass trial, the extrapolated position of the target at the time when the gate appears ($t + 300$) must be beyond the position of the gate. The probability of this occurrence is expressed below as the portion of the $p(v,t)$ distribution that falls beyond the corresponding z-score:

$$\begin{aligned} P(\text{'pass'|pass}, v, t) &= P[p(v, t+300) \geq vt] \\ &= P[z \geq [vt - v(t+300)]/s_1(t+300)] \\ &= P[z \geq -(v/s_1)300/(t+300)]. \end{aligned}$$

The probability of responding 'pass' on a no-pass trial is derived in a similar way. A 'pass' response will be given if the extrapolated target position at $t - 300$ is further than the gate position:

$$\begin{aligned} P(\text{'pass'|no-pass}, v, t) &= P[p(v, t-300) \geq vt] \\ &= P[z \geq [vt - v(t-300)]/s_1(t-300)] \\ &= P[z \geq (v/s_1)300/(t-300)]. \end{aligned}$$

Model 2 (unsteady tracker): According to this model, the extrapolation interval $[0,t]$ is subdivided into n intervals of time h. Tracker velocity V for each interval is sampled from a distribution with mean v and standard deviation s. Extrapolated position at time t is then:

$$p(v,t) = V_1 h + V_2 h + \cdots + V_n h.$$

The mean and variance of this distribution are:

$$\begin{aligned} E[p(v,t)] &= E[V_1 h + V_2 h + \cdots + V_n h] \\ &= E[V_1 + V_2 + \cdots + V_n]h = nvh = vt (\text{since } t = nh), \\ \operatorname{var}[p(v,t)] &= \operatorname{var}[V_1 h + V_2 h + \cdots + V_n h] \\ &= \operatorname{var}[V_1 + V_2 + \cdots + V_n]h^2 = ns^2h^2. \end{aligned}$$

Using $h = t/n$ and replacing s^2h with new variance s_2^2 yields:

$$\operatorname{var}[p(v,t)] = s_2^2 t.$$

Then predictions can be derived as for model 1:

$$\begin{aligned} P(\text{`pass'}|\text{pass}, v, t) &= P[p(v, t+300) \geq vt] \\ &= P\left[z \geq [vt - v(t+300)]/s_2(t+300)^{1/2}\right] \\ &= P\left[z \geq -(v/s_2)300/(t+300)^{1/2}\right]. \end{aligned}$$

$$\begin{aligned} P(\text{`pass'}|\text{no-pass}, v, t) &= P[p(v, t-300) \geq vt] \\ &= P\left[z \geq [vt - v(t-300)]/s_2(t-300)^{1/2}\right] \\ &= P\left[z \geq (v/s_2)300/(t-300)^{1/2}\right]. \end{aligned}$$

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