Systematic variation in performance of an interceptive action with changes in the temporal constraints

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People are highly skilled at intercepting moving objects and are capable of remarkably accurate timing. The timing accuracy required depends upon the period of time for which contact with a moving target is possible—the “time window” for successful interception. Studies of performance in an experimental interception task that allows this time window to be manipulated suggest that people change aspects of their performance (movement time, MT, and movement speed) in response to changes in the time window. However, this research did not establish whether the observed changes in performance were the results of a response to the time window per se or of independent responses to the quantities defining the time window (the size and speed of a moving target). Experiment 1 was designed to resolve this issue. The speed and size of the target were both varied, resulting in variations in the time window; MT was the primary dependent measure. Predictions of the hypothesis that people respond directly to changes in the time window were verified. Predictions of the alternative hypothesis that responses to changes in target speed and size are independent of one another were not supported. Experiment 2 examined how the type of performance change observed in Experiment 1 was affected by changing the time available for executing the interception. The time available and the target speed were varied, and MT was again the primary dependent measure. MT was smaller when there was less time available, and the effect of target speed (and hence the time window) on MT was also smaller, becoming undetectable at the shortest available time (0.4 s). The results of the two experiments are interpreted as providing information about the “rule” used to preprogramme movement parameters in anticipatory interceptive actions.

When intercepting a moving target the timing of movement is important: It is not only necessary to get to the right place to contact a moving target, you must also get there at the right time. The intercepting effector (such as a hand or a bat) must arrive at the interception location at the same time as the target. There will be some tolerance for error in this requirement...
for temporal coincidence. The tolerance depends upon various factors such as the size and speed of the target, the size of the intercepting manipulandum, and the way the task is executed (McLeod, McLaughlin, & Nimmo-Smith, 1985; Senot, Provost, & McIntyre, 2003; Tresilian & Lonergan, 2002). This can be most easily appreciated by consideration of the simple hitting task illustrated schematically in Figure 1.

In the task illustrated in Figure 1, a manipulandum is moved along a fixed, straight path perpendicular to the path of the moving target. The earliest moment at which the target can be struck by the manipulandum occurs when the target’s leading edge (right) is contacted by the left hand edge of the manipulandum. The last moment at which it can be struck occurs when the target’s trailing edge is contacted by the right hand edge of the manipulandum. The period of time between these two contacts defines a window of time during which it is possible to hit the target—the time window (Tresilian & Lonergan, 2002). During this period the target has moved through a distance equal to its length (L) plus the width of the manipulandum (W) at a speed V. The time window is therefore equal to \( \frac{L + W}{V} \). If the person were trying to strike the middle of the target with the middle of the manipulandum, then to strike the target movement timing would need to be accurate to within \( \frac{1}{2} \left( \frac{L + W}{V} \right) \).

These considerations show that the temporal accuracy required to intercept a moving target is determined by task variables. It should be noted, however, that if the performer is not constrained to move along a fixed path (as in Figure 1), it is possible to move with or pursue the target (move parallel to its direction of motion)—a movement strategy that can reduce the temporal accuracy required by widening the time window (Tresilian & Lonergan, 2002).

Not only do interceptive tasks demand a certain accuracy of movement timing, they also constrain the time available for performance. In the task illustrated in Figure 1, the performer first sees the target when it is a distance Z from the interception zone. If the target moves at constant speed (V), then there is a limited time between its first appearance and its arrival at the interception location, which is equal to \( \frac{Z}{V} \). The movement response must be prepared and executed during this period. The available time \( \frac{Z}{V} \) will be referred to as the viewing time (VT).

![Figure 1. Interceptive aiming task: A target (black) of length L moves with speed V along a straight track. A person attempts to strike the target with a hand-held manipulandum of width W by moving it along a straight track perpendicular to the target’s path. The manipulandum must move through a distance D to contact the target. The target can be struck whilst it is within the strike zone. It is within this zone for a time \( \frac{L}{V} \), the “time window”.](image-url)
Thus, performance of an interceptive task such as that shown in Figure 1 is temporally constrained in two ways: (a) Temporal coincidence of the intercepting effector with the target must be accurate to within the error tolerance of the task (the time window in Figure 1), and (b) the time available for preparation and execution of the movement is limited (the viewing time in Figure 1). As a result it would be expected that performance of an interceptive action would be influenced by these two constraints. This expectation has been confirmed by experiments. The reported effects of altering the time available are not difficult to understand: People respond to a reduction of the VT by starting their movements at a shorter time before the target reaches the interception zone (time-to-contact, TTC; Ball & Glencross, 1985), and so their movements are of shorter duration (shorter movement time, MT; Laurent, Montagne, & Savelsbergh, 1994; Montagne, Fraisse, Ripoll, & Laurent, 2000). In effect, as VT decreases people have to squeeze their preparation time and movement time into a shorter period (see Figure 2).

The effect of altering the time window is not completely clear (see below) but the data are consistent with demands for greater temporal accuracy and precision being responded to by the production of movements of shorter duration and greater speed (see Tresilian & Lonergan, 2002, for discussion). In a recent series of studies we have investigated the effects of manipulating the variables defining the time window (target speed, V, length, L, and strike manipulandum width, W) on performance of the interception task shown in Figure 1 (Tresilian & Lonergan, 2002; Tresilian, Oliver, & Carroll, 2003). People were found to make briefer and/or faster movements when the target’s speed (V) was greater, when its length (L) was smaller, and when the manipulandum width (W) was smaller. These results suggest that when people need to be more temporally accurate and precise (the time window is narrower), they produce briefer and faster movements. This suggestion is consistent with earlier experiments in which participants were required to make aimed movements to stationary targets in movement times.

![Figure 2](image_url). Temporal sequence of events associated with striking the target in Figure 1. Time runs horizontally as indicated by the thick shaded arrow. At some point in time the target becomes visible to the participant; a little later the stimulus that triggers the movement generation process becomes available (initiating stimulus). This stimulus is processed by the nervous system (processing time), and motor command signals are generated in response and sent to the muscles (transmission time). Shortly after these signals arrive at the muscles movement starts, and finally the target is struck. The diagram shows the minimum time required to complete this process (RT + MTmin). The initiation window is the difference between the viewing time (VT) and (RT + MTmin).
prescribed by the experimenter (e.g., Newell, Hoshizakio, Carlton, & Halbert, 1979; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). It was found that the variability of MTs in such experiments increased with the required MT: Movements could be executed in the required MT rather precisely when that time was short, but became increasingly less precise as the required MTs increased. This suggests that MT is more controllable when it is short, which would mean that greater temporal accuracy and precision could be achieved for shorter duration movements. This point is returned to in the General Discussion section.

The results outlined in the last two paragraphs suggest that the performance of interceptive actions is affected by both the time available and the demands for temporal accuracy and precision. Existing results, however, leave certain issues unresolved. The experiments reported here were designed to investigate two of these. First, in our earlier experiments it was found that target speed had a much larger effect on movement (its duration and speed) than did either target length (L) or manipulandum size (W) when the change in time window was the same (Tresilian & Lonergan, 2002). This difference was subsequently found to be due to an effect of target speed that was independent of the time window (Tresilian et al., 2003). The experiments reported in Tresilian et al. suggested that the target’s speed (V) and length (L) might have independent (additive) effects on MT rather than an interactive effect (via the time window). The purpose of the first experiment reported below was to determine whether L and V have purely additive effects on MT or whether they act through the time window. Second, it seems plausible to suggest that the two temporal constraints (viewing time and temporal accuracy demand) will interact in their effects on performance. The form of such an interaction has not been investigated. The reason for expecting an interaction can be appreciated with reference to Figure 2. Figure 2 shows that VT would be expected to have a strong influence on how much a person can vary their MT in response to changes in the time window or other task demands. Performance of an interception requires the person to make a decision concerning when to begin moving. Suppose that a person can make the interceptive movement in no less than a certain minimum movement time (MT_{min}). Following the target’s appearance the soonest a person could start to move is after one simple reaction time (RT—defined as the shortest time required to initiate a movement following presentation of the moving stimulus). If the VT were equal to MT_{min} plus the RT, then the person would have no choice but to initiate the movement one RT after the target appears. If the VT were greater than RT + MT_{min}, then the person would have a choice: They could either wait until the remaining VT was equal to RT + MT_{min} or they could move slower and initiate the movement correspondingly sooner. The RT is shown in Figure 2 as having three components: The processing time is the time it takes to extract the initiating stimulus information from the retinal images of the moving target and make it available to the motor control system. The transmission time is the time taken for the motor command signal to influence the muscles. Finally, it takes a short time for the limb to begin moving following activation of the muscles (the neuromotor lag). In Figure 2, the VT is greater than RT + MT_{min} by an amount labelled “initiation window”. In effect, the initiation window is the period of time between the first view of the moving target and the last moment the visual stimulus can be used to initiate an interceptive movement. The closer the VT to the minimum value (RT + MT_{min}) the smaller the initiation window, and there will be correspondingly less possibility for variation in MT. Thus, it might be predicted that the effect of other task
variables influencing MT (target speed, target length, manipulandum width) would be smaller for shorter VTs. This question was investigated in Experiment 2.

EXPERIMENT 1

Experiment 1 examined the effects of varying two quantities defining the time window—target length (L) and speed (V)—whilst keeping the VT relatively large to allow the possibility for appreciable variation in MT. The task shown in Figure 1 was used so that the time window and VT could be independently manipulated. The purpose was to determine whether target size and speed independently affect performance or whether they act in combination through the time window. If they act in combination, this would imply that people explicitly represent the temporal precision constraint (time window) and use it to determine aspects of their performance.

In the experiment, the speed and length of the target were both varied with four values of V and four values of L, giving a total of 16 combinations. Figure 3 shows graphically the

![Figure 3](image-url)

Figure 3. Qualitative pattern of results in the experiment (four target lengths by four target speeds) predicted by three hypotheses. Different symbols are associated with different target speeds: speed ▲ > speed ▼ > speed ● > speed ○. Hypothesis 1 (left): MT is directly proportional to the time window with no independent effects of speed or length. Hypothesis 2 (middle): MT directly proportional to target length and directly proportional to target speed (no interaction between the two). Hypothesis 3 (right): MT is directly proportional to the time window with an independent (additive) effect of target speed. Top row: MT plotted as a function of target size. Bottom row: MT plotted as a function of time window (arbitrary units on both axes).
expected results of such an experiment according to three hypotheses concerning the possible effects of the independent variables (V and L) on MT. Hypothesis 1 (Figure 3, left) states that L and V affect MT only through the time window—that is, MT is directly proportional to (L + W)/V. This first hypothesis is not consistent with the results from Tresilian et al. (2003), but the second and third are. Hypothesis 2 (Figure 3, centre) states that the time window has no effect and that MT is independently proportional to V and L. Hypothesis 3 (Figure 3, right) states that MT ∝ (L + W)/V and that V has an additional additive effect on MT that is independent of the time window. The graphs in the top row of Figure 3 show MT as a function of target length L. The graphs in the bottom row are of MT as a function of the time window. The patterns of results predicted by the three hypotheses are clearly very different. The experiment should, therefore, allow them to be distinguished.

As described earlier, the time between first seeing the moving target and it entering the strike zone (called the viewing time, VT) imposes an important temporal constraint on interception. Several authors have previously drawn attention to the fact that if the viewing distance (Z) is held constant and the target speed varied, then the faster target speeds will be associated with shorter VTs (e.g., Ball & Glencross, 1985; Mason & Carnahan, 1999). As Mason and Carnahan noted, when the VT is shorter a person is likely to make briefer, faster movements because there is less time available, not because the target is moving faster. Empirical results have confirmed this (Ball & Glencross, 1985; Laurent et al., 1994; Mason & Carnahan, 1999; Montagne et al., 2000). Thus, it is critical to avoid covarying target speed and VT if effects of target speed independent of VT are to be observed. The strategy adopted in Experiment 1 was to keep VT relatively large (1.6 s) compared to MT and constant over changes in target speed. The consequence of this strategy is that target speed covaries with viewing distance (Z) rather than VT. This raises the possibility that any effects of target speed on performance could actually be effects of the changes in viewing distance. Previous experiments have shown that VT and/or target speed affect performance (Ball, 1992; Ball & Glencross, 1985; Brouwer, Brenner, & Smeets, 2000, 2002; De Lussanet, 2001; Fleury, Basset, Bard, & Teasdale, 1998; Laurent et al., 1994; Mason & Carnahan, 1999; Montagne et al., 2000) but have not shown any independent effect of viewing distance, leading to the conclusion that it is not viewing distance that affects performance but VT (e.g., Fleury et al., 1998; Mason & Carnahan, 1999; Montagne et al., 2000), target speed (e.g., Brouwer et al., 2000, 2002), or both (e.g., Ball & Glencross, 1985). Furthermore, whilst it is relatively straightforward to give functional interpretations to the finding that shorter VTs and faster targets elicit briefer, faster responses (see above and Discussion section), it is not easy to explain why greater viewing distances should elicit briefer, faster responses. For these reasons, any effects of changing target speed that are observed in the experiment will be assumed not to be due to the associated changes in viewing distance. Note that if this assumption is true, it is still possible for participants in experiments of the type reported here to learn to use viewing distance as information about target speed (and/or the target’s time to arrival) since these variables are perfectly correlated. Thus, although target speed would be the variable that influences performance, participants could learn the relationship between distance and speed, and since the former is available to them before they see the target they could get an early estimate of target speed. However, the issue of what sources of information are being used is beyond the scope of the experiments reported.
Method

Participants

A total of 5 men and 3 women (age range 22–34 years; mean = 28 years) participated voluntarily in the experiments and gave their informed consent prior to commencement of the testing sessions. All were either staff or students at the University of Queensland and had normal or corrected-to-normal vision. Their handedness was assessed using a modified version of the Edinburgh Handedness Inventory (White & Ashton, 1976) administered verbally. All were right-handed.

Apparatus

The same experimental apparatus was used in all experiments and followed the schematic of Figure 1. A computer controlled torque motor was used to drive a 25-mm wide belt around two pulleys 4 m apart. The top of the belt rested on an aluminium support and stood 1.2 m above the floor. Four targets were constructed of rigid plastic material 3 mm thick and 50 mm tall covered with bright orange adhesive vinyl; the length (L) was varied taking the values 41, 75, 111, 141 ± 0.5 mm. Targets were attached by small magnets to a black support block 25 mm tall by 25 mm wide by 80 mm long fixed to the drive belt with double-sided tape. Targets were driven at predetermined constant speeds (1,000, 1,417, 1,800, 2,200 mm/s) along the track following an initial acceleration during which the target covered a distance of 340 mm (the target was not visible during this acceleration period). Target speed could be specified to within ±10 mm/s. Details of the apparatus are presented elsewhere (Tresilian & Lonergan, 2002; Tresilian et al., 2003).

The manipulandum was composed of a handle mounted on a square aluminium block. The block housed a bearing, allowing it to be slide freely along a straight track mounted 110 mm above the drive belt. The target was struck by a rigid steel rod, 5 mm in diameter, mounted vertically on the front the block. Thus W in Figure 1 was always 5 mm. To strike the target the manipulandum had to be moved through a distance (D) of 22 cm. Infrared light emitting diodes (IREDs) were fixed to the target base and to the top of the handle of the manipulandum. The positions of these IREDs were sampled at 500 Hz during experimental trials using an Optotrak™ (Northern Digital Inc.) optoelectronic movement recording system and stored on computer disk.

VT was kept constant at 1.6 s, and so slower moving targets were seen moving over shorter distances than faster targets. The distances the target moved between the moment it was first visible to the participant and its entry to the strike zone were changed using a moveable occluder mounted on a linear slide running parallel to the drive belt. The occluder had a flap-door (made of black cotton strips) through which the target emerged.

Procedure

A total of 10 experimental trials in each condition were conducted (160 total) and run in two sessions of 80 trials on consecutive days, with 5 trials in each condition in each session presented in pseudorandom order. Prior to each experimental session, every participant performed a practice session. The practice sessions began with an easy condition (largest target at the slowest speed) and then incrementally increased in difficulty in six steps to the smallest target at the fastest speed. In each practice condition participants performed as many trials as required to perform four successful hits in a row. Following a short break (about two minutes) the experimental trials began.

Whether or not participants struck the target was noted by the experimenter on each trial. Participants were required to strike at least 70% of targets in each condition. If performance dropped below 70% trials were re-run at the end of the session. In the event, participants made few errors. Data from trials on which participants missed the target were not included in the main analysis. Procedures were approved by the Ethics Committee of the University of Queensland.
**Data reduction and analysis**

The position data time series were digitally filtered (dual pass through a second-order Butterworth filter with a 20-Hz cut-off), and the filtered data were used for further analysis. Details of the analysis procedures and algorithms are given elsewhere (Tresilian & Lonergan, 2002; Tresilian et al., 2003). The dependent measures were movement time (MT, time between movement onset and target strike) and maximum movement speed (V_{max}, greatest speed reached up to and including the moment of striking the target). For each participant the mean of the 10 trials in each experimental condition were averaged to a MT and a V_{max} estimate for each condition. Statistical reliability of the effects of experimental manipulations on these measures was assessed using analysis of variance (ANOVA) and linear regression.

**Results**

Statistically reliable effects of both target length, \(F(1.2, 8.3) = 10.2, p < .05\), and speed, \(F(1.6, 11.2) = 17.5, p < .01\), were found, and there was a reliable interaction between length and speed, \(F(3.4, 23.5) = 3.0, p < .05; \)\(df\)s have been corrected for inhomogeneity of variance using Huynh–Feldt’s method (e.g., Keppel, 1982) when Mauchly’s test of sphericity was failed. The interaction is predicted by the hypothesis that MT is proportional to the time window, and the additive main effect of speed means that the data are consistent with the third hypothesis described in the Introduction (Figure 3, right panels). However, a significant main effect of speed is not sufficient to distinguish the hypothesis that MT depends upon the time window alone (Hypothesis 1) from the hypothesis that MT depends upon the time window with an additional additive effect of speed (Hypothesis 3)—a speed main effect is also likely to be present if the data are of the form shown in Figure 3, top left (Hypothesis 1). The group mean MT data are plotted in Figure 4a as a function of target length for the four different speeds. This plot is of the form predicted by Hypothesis 3 (Figure 3, top right) and so suggests that this hypothesis better describes the results than does Hypothesis 1.

As shown in Figure 3 (bottom right), the third hypothesis predicts that the slopes of the relationships for the different speed conditions should be approximately the same when plotted as a function of the time window. Hypothesis 2 (that MT is not influenced by the time window but by L and V independently) predicts that the slopes should be different—steepest for the fastest target and shallowest for the slowest, with the MT shortest overall for the fastest target and shortest for the fastest (Figure 3, centre bottom). Hypothesis 1 predicts that all the data points should fall on the same line when plotted as a function of the time window. Figure 4b plots the group mean MT data as a function of the time window: The pattern is clearly consistent with Hypothesis 3 but inconsistent with Hypotheses 1 or 2, as expected given the ANOVA results reported in the previous paragraph.

The extent to which Hypothesis 3 describes the data was further assessed by two sets of linear regressions for each of the 8 individual participants, one set regressing MT against time window and a second regressing MT against target height. Each set of regressions yielded a slope and an intercept for each of the four speed conditions for each participant. The mean slopes and intercepts (\(\pm 1SE\)) from the regressions of MT against time window are shown plotted as a function of target speed in Figure 4c and d. The slopes and intercepts were always positive (as predicted by Hypothesis 3). Both slope and intercept data were analysed using ANOVA. There was no statistically reliable effect of target speed on
the slope, consistent with Hypothesis 3, $F(3, 21) = 1.34, p > .05$, and the graph in Figure 4c shows that the slopes at different speeds had similar values. The effect of speed on the intercept was reliable, $F(3, 21) = 5.11, p < .01$, which confirms the existence of an additive effect of target speed on MT that is independent of the time window. The regressions of MT against time window are thus consistent with Hypothesis 3, but the absence of a reliable effect of speed on the slope does not offer strong support for the hypothesis since unreliable effects cannot be unequivocally interpreted. Stronger support would be provided by a significant effect of speed on the slope of the MT–target size relationship with a reliable linear trend for slope to increase with decreasing target speed. This support was provided by the second set of regressions (MT on target size), which revealed a reliable effect of speed on the slope, $F(3, 21) = 4.951, p < .01$, and a significant linear trend in the expected direction, $F(1, 7) = 6.8, p < .05$. Thus, the data strongly support Hypothesis 3 over both Hypothesis 1 and Hypothesis 2 and confirm that the data follow the pattern predicted by Hypothesis 3.

Note that the data do not allow the form of the dependence of MT on target speed to be uniquely defined—the results are consistent with either an inverse proportional relationship (MT $\propto 1/V$) or a directly proportional relationship (MT $\propto V$) with MT decreasing as $V$ increases. Previous experimental data (Tresilian & Lonergan, 2002; Tresilian et al., 2003)
marginally favoured inverse proportionality, though direct proportionality could not be ruled out. Over the range of speeds used in these experiments, the inverse and direct proportional relationships between MT and target speed appear to describe the data almost equally well.

Maximum movement speed ($V_{\text{max}}$) increased monotonically with increases in target speed and decreased monotonically with increasing target size (Figure 5a). Both effects were statistically reliable: For target speed, $F(1.12, 7.85) = 31.7, p < .01$; size, $F(1.14, 8.5) = 15.9, p < .05$; dfs corrected by Huynh–Feldt's method. There was no reliable interaction between target speed and size in their effect on $V_{\text{max}}, F(9, 63) = 0.93, p > .05$. The effect of target size on $V_{\text{max}}$ is almost linear for the mean data shown in Figure 5(a). This is similar to the results of previous studies (Tresilian & Lonergan, 2002; Tresilian et al., 2003). The effect of target speed shows evidence of a saturating nonlinearity, probably due to the fact that $V_{\text{max}}$ must have some upper limit.

Since both dependent measures (MT and $V_{\text{max}}$) change systematically with changes in the independent variables, a question arises concerning whether a change in one dependent measure (e.g., $V_{\text{max}}$) is a consequence of a change in the other (MT). Thus, it is possible that a person controls just one variable (e.g., MT), and the other changes as a consequence. In this case, it is useful to know which variable is being controlled (MT or $V_{\text{max}}$). Alternatively both variables might be being controlled as has been suggested for temporally constrained aiming (Newell et al., 1979). For interceptive actions of the type being studied in the experiments reported here, a successful outcome (target strike) is achieved if the intercepting effector arrives at the strike location at the same time as the target (within the limits defined by the time window). Thus, the basic condition for interception is a temporal one—the time remaining until the effector reaches the interception location must be equal to the time remaining until the target arrives there. In order to achieve this condition it makes sense to control movement time rather than speed (cf. Lee, 1980; Poulton, 1950; Tyldesley & Whiting, 1975). Thus, the view taken here is that MT is the primary controlled variable, a point returned to in the General Discussion section.

![Figure 5. Mean maximum speed ($V_{\text{max}}$) data from Experiment 1. (a) Mean values of $V_{\text{max}}$ as a function of target size for the four speed conditions (indicated next to the corresponding plot in m/s). (b) Mean standard deviation of the $V_{\text{max}}$ data for the four speed conditions.](image-url)
EXPERIMENT 2

As described earlier, the size of an effect of the task parameters (specifically V and L) on MT is likely to be small when the VT is small. What is unclear is exactly how VT affects the relationship between MT and the task parameters. Experiment 2 examined the effect of VT on the relationship between performance (MT and peak speed) and one of these parameters (target speed, V) in the hitting task (Figure 1). Target speed was varied in the experiment as this parameter has been established to have a larger effect on MT than either target length or manipulandum size, and it allowed a further evaluation of whether the independent, additive effect of target speed on MT is better described as inversely or directly proportional.

It is fairly obvious that when VT is sufficiently short, MT will have to be as brief as possible if the target is to be struck. In this case there should be no effect of target speed on MT. A very short VT (400 ms) was used as one of the experimental conditions, and it might be expected that this would be short enough to eliminate the effect of V on MT (see Introduction). Of more interest is how people respond as the VT is increased to larger values. For example, they might display a systematically increased effect of V on MT as VT increases. To evaluate this possibility a range of VTs between 400 and 1000 ms were examined.

Method

Participants

A total of 4 men and 2 women participated voluntarily in the experiment and gave their informed consent prior to testing. All were either staff or students at the University of Queensland and had normal or corrected-to-normal vision. Their handedness was assessed using the modified Edinburgh handedness administered verbally. All were right-handed. Ages ranged from 22 to 34 years (mean = 26 years).

Apparatus

The apparatus and recording were the same as those for Experiment 1 except that the drive belt was masked by a vertically mounted sheet of black rigid card that ran the length of the trackway. This prevented participants from seeing the motion of the drive belt prior to the emergence of the target from behind the occluder. During testing participants wore muffling headphones that masked the noise of the drive belt and motor. These precautions reduced the likelihood that participants would be able to predict the appearance of the target by either seeing or hearing the motion of the drive belt. Prediction was further prevented by arranging for the period following the start of the belt’s motion and appearance of the target to take at random one of six possible values. VT was manipulated by positioning the occluder so that its distance from the strike zone divided by the target speed equalled the desired VT (to within ±10 ms). A single target of length L = 60.2 mm and height 50 mm was used.

Procedure

The target was moved at four different speeds (1,000, 1,330, 1,670, and 2,000 mm/s), and VT could take one of five values (400, 500, 600, 800, and 1,000 ms). The target was moved at all four speed speeds in each of the five VT conditions, and so there were 20 experimental conditions in all. In the experimental session six experimental trials were conducted in each of the 20 conditions in a pseudorandom
order that was different for each participant (fully randomized repeated measures design). Prior to the experimental session, all participants performed a practice session, which began with trials at $V = 1,000 \text{ mm/s}$, $VT = 400 \text{ ms}$, then at $V = 1,330 \text{ mm/s}$, $VT = 500 \text{ ms}$, then $V = 1,670 \text{ mm/s}$, $VT = 600 \text{ ms}$, then $V = 2,000 \text{ mm/s}$, $VT = 800 \text{ ms}$, and finally $V = 2,000 \text{ mm/s}$, $VT = 400 \text{ ms}$. In each practice condition participants performed as many trials as required to perform four successful hits in a row. The task and instructions were identical to those in Experiment 1.

Results

Figure 6a shows the overall mean MTs (averaged over participants) in each VT condition plotted as a function of target speed. The main effect of target speed was statistically reliable, $F(2.1, 10.3) = 24.4, p < .01$, as was the main effect of VT, $F(1.66, 8.28) = 26.9, p < .01$, and the interaction between target speed and VT, $F(7.7, 38.5) = 4.4, p < .01$; all df's have been corrected by Huynh–Feldt's method. Figure 6b shows the overall mean MT variability (average of the individual participant variability in each condition) plotted in the same way as the data in panel (a). The data showed no tendency to conform to an inverse proportional form for the relationship between speed (V) and MT, suggesting instead the (negative) directly proportional relationship.

Inspection of Figure 6a suggests that the statistically reliable interaction between target speed and VT was due to the slope of the relationship between MT and target speed being largest when the VT time was longest and smallest when the VT was shortest. This was further analysed by conducting linear regression analyses on the individual participant data in each VT condition: MT was regressed on target speed to give a slope and an intercept. The results are shown in Figure 6c and d: (c) plots the slopes obtained in each VT time condition for each individual participant (small symbols, thin lines) and the average of these individual results (large circular symbols, thick solid line). The intercepts from the regression analyses are plotted in Figure 6d. The average plot shows a systematic effect of VT on both the slope and the intercept. All individual participant intercept data followed the mean pattern (Figure 6d), but there was some variability in the individual slope data (Figure 6c). The effect of VT on the slope was statistically reliable, however, $F(4, 20) = 6.55, p < .01$, and there was a reliable linear trend in the expected direction, $F(1, 5) = 9.53, p < .05$.

Individual participant regression results were statistically significant for slopes greater than about 0.03 ms/(mm s$^{-1}$) in magnitude. Slopes between −0.03 and 0.03 were not statistically reliable ($p > .05$); with only two exceptions, these occurred for the shorter VTs between 400 and 600 ms. The average plot in Figure 6c shows a systematic steepening of the slope with increasing VT, and this pattern is reflected to some extent in all the participants except one (Participant 3, ▼ in Figure 6c). This participant’s slopes became steeper over the 400, 500, and 600-ms VTs but shallower again for the 800 and 1,000-ms VTs. This participant also produced the shortest MTs of all participants in the 400-ms VT condition and was the only participant to produce a statistically reliable relationship between MT and target speed in this VT. The magnitude of the slopes for the MT–target speed relationship for Participant 3 had the smallest range of all participants: between 0.04 and 0.075 ms/(mm s$^{-1}$).

Other work has identified VT as the primary determinant of MT and movement speed (Mason & Carnahan, 1999; Montagne et al., 2000) and has suggested that target-related variables have little influence on these aspects of performance. This is clearly at odds with the
data of Experiment 1 and previous experiments (Tresilian & Lonergan, 2002). We previously argued that these apparently conflicting results can be reconciled if effects of target speed can only be reliably observed when the VT is sufficiently large. The results of this experiment provide a clear demonstration of this.

The data shown in Figure 6 also provide some additional evidence in favour of the claim made in the Introduction that it is VT and target speed that affect performance in these tasks rather than the viewing distance (Z, Figure 1). Figure 6a shows that as VT increased so MT
increased (independent of target speed), and it also shows that as target speed increased MT decreased (independent of VT). In this experiment, for a particular VT, increases in target speed were associated with increases in viewing distance. Thus, if it were to be argued that viewing distance rather than speed were responsible for MT changes, then we would conclude that larger viewing distances lead to shorter MTs. However, this conclusion is contradicted by the finding that MT was larger for longer VTs, since longer VTs were associated with increased viewing distances. Here we would conclude that larger viewing distances lead to longer MTs. The most parsimonious interpretation of the findings is that people respond to increased VTs by making longer duration movements, whereas they respond to increased target speed by making shorter duration movements.

GENERAL DISCUSSION

Experiment 1 showed that target length (L) and speed (V) have an interactive effect on MT in the interceptive task studied here. The form of this interaction supports the hypothesis that MT is directly proportional to the time window, \((L + W)/V\). Thus, it can be concluded that L and V affect MT in combination through the time window variable, indicating that people make use of an explicit estimate of the time window for controlling the duration of their responses. The data also supported the existence of an effect of target speed on MT that is independent of the time window. The simplest form for this dependency that is consistent with both Experiment 1 and Experiment 2 is a directly proportional relationship between MT and V, with MT decreasing as V increases. The group mean data from Experiment 2 (Figure 6a) favour the directly proportional relationship. Thus, the data from Experiment 1 can be best summarized by a simple relationship between the dependent and independent variables as follows:

\[
MT = a + b([L + W]/V) - cV
\]

where \(a\)–\(c\) are positive empirical constants, and \(W\) was constant in the experiment (though it appears to have an equivalent effect to \(L\), Tresilian & Lonergan, 2002). This relationship is simply a statement of Hypothesis 3 (Figure 3, right-hand column) and produces the pattern of results found in Experiment 1 (Figure 4 a, b).

If Equation 1 is supplemented by the additional empirical finding that for interceptive actions, MT is directly proportional to the distance that must be covered to intercept the target (D in Figure 1a; Schmidt, 1969; Tresilian & Lonergan, 2002; Zaal, Bootsma, & van Wieringen, 1999), then existing results can be summarized by the following relationship between the MT and the independent variables L, V, D, and W:

\[
MT = a + b([L + W]/V) - cV + dD
\]

In addition to summarizing the results of Experiment 1 in combination with previous findings, Equation 2 can be viewed as a hypothesis concerning the quantitative relationship between MT and the independent variables. The qualitative fit is very good but whether Equation 2 provides an exact quantitative fit depends upon at least three matters that remain unresolved:

1. Whether the independent effect of speed is described by a direct or inverse proportional relationship. Over the range of speeds used, the directly proportional form adequately
describes the data, but to decide the matter, a greater range of speeds than that used here will be required.

2. Whether there is an effect of target speed on the relationship between MT and time window. The data from Experiment 1 did not support any such effect, but lack of significance in a statistical test is not, in itself, evidence of no effect.

3. Whether there is any interaction between distance moved (D) and target speed and/or time window. This possibility has not yet been tested empirically.

At this stage, therefore, Equation 2 represents a summary of existing results whose ability to give an accurate, quantitative description of performance will need further study to evaluate. Assuming that the description is accurate, three questions can be raised concerning the significance of the description (Equation 2): (a) What does Equation 2 tell us about the control of interceptions? (b) Why is MT related to the task variables in the manner described by Equation 2? (c) To what extent do the results summarized by Equation 2 apply to other interceptive tasks?

What does Equation 2 tell us about the control of interceptions?

MTs of the hitting movements in the experiments reported were very short, ranging from about 80 ms to 400 ms for individual participants; the mean MTs were always less than 240 ms in Experiment 1 and always less than 280 ms in Experiment 2. Given the relatively long time it takes for visual feedback information to influence a manual response—in the order of 100–150 ms (see Paillard, 1996)—any feedback correction of many of the movements produced in the experiments seems unlikely. This is especially so in the conditions that demanded high temporal precision where a greater need for corrections might be expected but the MTs were shortest. Even if there were sufficient time to use on-line visual feedback to alter a movement, such alterations would often have to be made relatively late, close to the moment of striking the target. The target is struck close to the moment of peak speed in these tasks (e.g., Montagne et al., 2000; Tresilian & Lonergan, 2002) when the limb has very high momentum (see Figure 5): To make alterations to movement speed at this time would require large muscular forces that would take significant time to develop. Work on temporally constrained aiming lends some further support to the idea that interceptive actions of the type studied here may not be influenced by feedback corrections. Carlton (1994) showed that when people tried to make an aimed movement last a particular time (400 ms) there was no evidence of corrections. Aimed movements of the same amplitude and spatial accuracy demands executed “as fast as possible” almost always showed evidence of at least one correction despite the average MT being less than 400 ms. This supports the contention that rapid aimed movements that need to be precisely timed are executed in a visually open-loop mode.

If the arguments of the previous paragraph are correct, and fast interceptive actions of the type studied in the two experiments reported here are executed without the use of online visual feedback, then movement timing must be accomplished by predetermining MT and the moment of movement initiation. If the target is to be intercepted then the intercepting effector must arrive in the strike zone when the target is in that zone (Figure 1). In
order to achieve this with an open-loop process, it is necessary to predetermine (or preprogramme) movement time and make sure that the movement is initiated at the right time. If the MT is defined as in the experiments reported—time between movement onset and target contact for a hit—then the right time to begin moving is when the target’s TTC with the strike zone is equal to the MT since this guarantees interception. If you want to start moving at this particular moment, it is necessary to issue the descending central motor commands a little earlier since these will take some time to reach the muscles and cause movement to begin. In Figure 2, this time is the transmission time plus the neuromotor lag.

To initiate the descending motor command at the right time requires information about the target’s TTC—a quantity people are known to be able to perceive (Gray & Regan, 1998; Regan & Hamstra, 1993; for review, see Tresilian, 1999). Extracting TTC from the stimulus and transmitting it to motor control centres takes time (processing time in Figure 2). Together the processing time, transmission time, and neuromotor lag add to give the simple RT (Figure 2). This means that the critical value of the target’s TTC that should be used to initiate motor commands (TTC\textsubscript{crit}) is equal to MT + RT. This will result in the movement beginning when the target’s TTC is equal to MT. Thus, once MT is determined, the value of TTC\textsubscript{crit} is also set (as MT + RT). This scheme for controlling the timing of interceptive actions is a development of an idea called effector anticipation (Poulton, 1950), which was later refined into the operational timing concept described by Tyldesley and Whiting (1975).

It has been suggested that the process could be simplified by making MT constant for a particular task (Fitch & Turvey, 1978; Lee, 1980). This means that MT does not need to be predetermined or preprogrammed prior to each performance—it has a fixed value that is stored in memory. Since the MT does not vary, then neither does the value of TTC\textsubscript{crit} that initiates the act. However, the data reported here show that MT is not constant but varies substantially and systematically with the task parameters—a finding confirmed by data from other tasks (e.g., Brouwer et al., 2000; De Lussanet, 2001; Gray, 2002; Zaal et al., 1999). In the task used here (Figure 1), the dependency of MT on the task parameters is described by Equation 2. Thus, Equation 2 can be interpreted as a direct reflection in performance of the “rule” used by the nervous system to preprogramme MT (under the assumption of visually open-loop control; Tresilian, 2003). For performance to vary systematically with the task parameters, the person must have access to information about the magnitudes of these parameters. Thus, the MT preprogramming process would require information about the distance to move (D), the speed of the target (V), and the combined “size” of the target and manipulandum (L + W). Note that in the experimental task information about D and W was available prior to seeing the target since the participant could see the manipulandum and so perceive its size and initial location; they could also see the track along which the target will move. There was also some information about V available since this is correlated with the viewing distance Z (as discussed in the Introduction). The availability of such advance information would allow participants to prepare themselves to make an appropriate response prior to actually seeing the moving target, something that has been found to significantly improve performance of interceptive actions of the types commonly found in sports such as baseball batting (Gray, 2002) and racquet sports such as squash (Abernethy, 1990).

Preprogramming MT is only half the problem; the person must initiate the movement at the right moment, and this requires detection of TTC\textsubscript{crit}. It is known that people can estimate
the TTC of a moving object using information available in the stimulus (as mentioned earlier in this section). The results of Experiment 2 suggest that TTC is not only essential for initiating movement, but is also important in the MT programming process. When the target becomes visible, its TTC at that time is an estimate of the viewing time and hence provides information about the time available for executing the movement. The results of Experiment 2 show that as less time is available, participants tend to reduce their MTs, and target speed has a smaller effect on MT. In terms of Equation 2, this translates into a reduction of the value of $a$ and of $c$ (and possibly $b$). The precise variation in these parameters with changes in VT depended upon the individual participant. All participants except Participant 3 responded to changes in VT with changes in both $a$ and $c$. Participant 3 showed little evidence of a change in $a$ but did show evidence for a change in $c$. This can be done provided the VT is not short enough to force the person to move at their fastest possible speed (reach MT$_{\text{min}}$). The results of Experiment 2 are consistent, therefore, with Equation 2 in which $a$, $c$, and/or $b$ depend upon the VT (as $D$ was not varied it is not possible to say anything about $d$).

Why is MT related to the task variables in the manner described by Equation 2?

An answer to this question can be provided based on the idea that a person adapts their performance so as to satisfactorily meet the demands of the task whilst simultaneously meeting another criterion related to the effort expended in making the movement. As noted in the Introduction, briefer, faster movements to stationary targets are associated with greater temporal precision (Carlton, 1994; Newell et al., 1979; Schmidt et al., 1979). Consistent with this, it has been found that when intercepting moving targets, the briefer movements produced in response to targets whose interception demands greater temporal precision (smaller time windows) are more temporally precise (Tresilian et al., 2003). Thus, when greater temporal precision is demanded by the task, a person responds by making a briefer, faster movement. The fact that a person covaries the speed and brevity of movement with the temporal precision demands means that when they are able to move more slowly they do, implying that people prefer not to move fast unless the task demands it. For this reason it is necessary to introduce the idea that another criterion related to effort expended is also governing performance (Tresilian et al., 2003). Although this explains why MT covaries with the time window as described by Equation 2, it does not explain the independent effect of target speed.

There is a reason for making briefer movements when the speed of the target is higher, regardless of the time window: A briefer movement allows a person to wait longer before starting to move (Tresilian, 2003). Waiting longer before moving allows more time to see the moving target, to obtain perceptual estimates of relevant variables such as target speed, size, and time-to-contact, and to preprogramme the movement. This has been suggested as the reason why professional baseball batters with the highest batting averages tend to be those with the shortest swing times (Breen, 1967). Viewing the target for longer, even only 50–100 ms longer, has been found to improve performance in some interceptive actions (Elliot, Zuberec, & Milgram, 1994; Sharp & Whiting, 1974, 1975). This is likely to be particularly significant for time-to-contact estimation if movements are executed visually open-loop, as suggested above. Gray and Regan (1998) showed that human observers are capable of very accurate (within 2%)
single estimates of TTC. The strategy of delaying movement onset by shortening MT is advantageous in this context. The later the movement is initiated, the smaller the values of TTC crit that is used as a trigger, and a smaller value has a smaller estimation error.

To what extent do the results apply to other interceptive tasks?

The simple hitting task used in the experiment reported here (Figure 1) constrained participants to move along a straight path, and so no choice was possible concerning the location of interception. This task was used because it allows the time window and the viewing time to be experimentally manipulated. If the participants were free to choose where to contact the target and could move parallel to the target as well as perpendicularly to it, then neither the VT nor the time window could be controlled: A person’s choice and movement strategy could also influence VT and the time window (see Tresilian & Lonergan, 2002). However, due to the constrained nature of the task, it is reasonable to ask how the results might apply to less constrained interceptive tasks.

The results are certainly consistent with results obtained in less constrained tasks in which experimental participants were free to choose the interception location and/or to move both parallel and perpendicular to the target. In such tasks, people have been found to make briefer and/or faster movements when the target moved faster (e.g., Brouwer et al., 2000, 2002; De Lussanet, 2001; Gray, 2002; Port, Lee, Dassonville, & Georgopoulos, 1997; Van Donkelaar, Lee, & Gellman, 1992) and when the VT was shorter (Laurent et al., 1994; Montagne et al., 2000). The data are also consistent with results from a variety of simple laboratory tasks involving button press/release responses in which timing has been found to be influenced by the size of a moving target: Larger targets elicit earlier responses, which correspond to longer MTs in interceptive tasks (DeLucia, 1991; Lopez-Moliner & Bonnet, 2002; Smith, Flach, Dittman, & Stanard, 2001). However, due to the unconstrained nature of the tasks involved, interpretation of the results is problematic: It is not possible to determine which variables were influencing performance and how these interacted with the strategy adopted by the performer (see, e.g., Ball & Glencross, 1985; Flach, Smith, & Stanard, 2002; Mason & Carnahan, 1999).

Thus, the results reported here are consistent with the results from less constrained tasks and allow the variables that influence performance to be identified. Furthermore, as described in the Introduction and earlier in this section, the results can be interpreted as adaptive responses to changes in the temporal constraints of the tasks. The extent to which the results apply to less constrained tasks depends upon what other factors influence performance in these tasks and how these interact with the temporal constraints. One factor that is likely to be particularly important in this respect is the requirement for spatial as well as temporal accuracy when intercepting a moving target (e.g., Regan, 1992). In the absence of temporal constraints, the normal response to a requirement for greater spatial accuracy in a target-directed aiming task is to increase MT (see, e.g., Plamondon & Alimi, 1997; Schmidt & Lee, 1999, for reviews). This is the opposite response to that made when greater temporal accuracy is required (Experiment 1; Newell et al., 1979). Thus, simultaneous requirements for both spatial and temporal accuracy might impose conflicting demands upon performance, suggesting that a trade-off would be necessary. If a person trades off temporal accuracy in favour of spatial accuracy, then the results reported here are less likely to be relevant to performance in such a task.
Whether such trade-offs exist and how people respond to demands for spatial accuracy in interceptive actions is presently unknown and remains an open question for future research.

In summary, the data reported here support the hypothesis that performance of anticipatory interceptions is systematically influenced by the time window, target speed, and viewing time. The data can be summarized by Equation 2. If the movements are performed visually open-loop, the results suggest that Equation 2 can be interpreted as a reflection of the rule that the nervous system predetermines the MT based on estimates of the task variables (L, V, D, W).

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