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RESEARCH NOTE

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Throwing darts: timing is not the limiting factor

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Abstract It has been argued that precision in throwing is limited by the precision in the timing of the release. When precision is the only goal, as in throwing darts, one could therefore expect people to throw in a way that reduces sensitivity for imprecision in timing. We show that subjects do not do so, but throw in a way that reduces the sensitivity for speed errors instead. They even appear to vary the timing of release to compensate for the errors in the hand's movement. Thus timing does not appear to be the limiting factor.

Keywords Human · Arm movement · Precision · Timing · Variability

Introduction

The aim of throwing darts is to let the dart end on a certain position on the board. Where a thrown dart will hit the board depends on the combination of position, speed and direction of motion at the moment that it is released. There are an infinite number of combinations of these variables that all lead to exactly the same final position of the dart on the board. There are also an infinite number of ways (movement strategies) that the hand could reach each such combination. Which of all these possibilities do subjects use? We assume that subjects try to find a movement strategy that is robust for imprecision. In order to determine how this could be achieved, we must know which combinations of position, speed, and direction of motion are appropriate.

To predict the final position of a dart that has been released, we make a simplification, and assume that the dart is essentially a point-mass. By making this assumption, we neglect the role of rotations and air resistance. In the horizontal plane, there are no forces that act perpendicular to the dart's motion after release, so the horizontal component of a dart's movement is a straight line. This means that the position and direction of the dart's motion at the time of release determine the horizontal position of the dart on the board, independent of the dart's speed. The speed of the throw is crucial for the vertical component, because the dart falls during its movement. If the throw is too slow, it takes more time for the dart to reach the board, and the dart will end too low. If the throw is too fast, the dart will end too high.

Errors in the position, speed, and direction of motion are not the only factor that we need to consider. In order to hit the target, the hand has to move along a trajectory that yields an appropriate combination of position, speed and direction of motion, but the dart also has to be released at the moment that this appropriate combination is reached. If the timing is wrong, the position on the board will usually be different. Figure 1a illustrates this with a side view of a dart thrower and a dartboard. If the hand moves at a constant speed along a circular path, the final position of the dart on the dartboard will depend on the time of release, as indicated with three examples of possible trajectories. An overview of a few real trials (Fig. 1b–d) gives an idea of a typical throwing strategy. The hand's path is in general close to (but not exactly) a segment of a circle (Fig. 1b), and the hand's speed is not constant, but increases until after release (Fig. 1c). The dart is released close to the zenith of the hand's path (Fig. 1d).

How much the final position of the dart changes with an error in the timing of release depends on the hand's trajectory. In this study, we will investigate how sensitive the movement outcome (the final position of the dart on the board) is for timing errors. We will do this both for hypothetical movement trajectories and for trajectories of the hand measured during actual throws. Such a sensitivity analysis of the hand's trajectory reveals how large the effect of a timing error is on the dart's final position on the dartboard. A similar sensitivity analysis will be used to reveal the effect of errors in other parameters of the throw,

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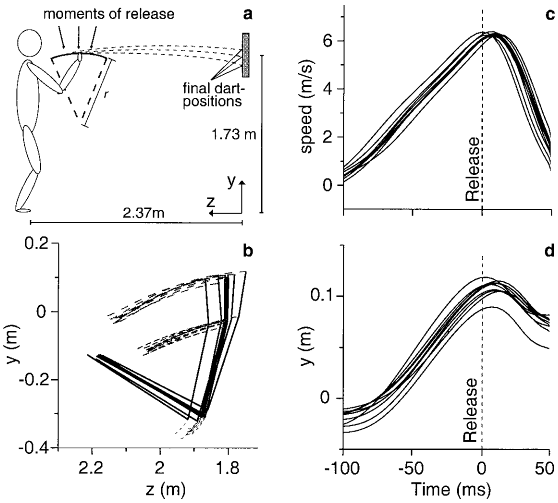

Fig. 1a–d Characterisation of how our subjects threw the darts. **a** Side view of a subject throwing darts. **b** A stick figure of the arm at the time of release for the first ten trials of subject S1 (*solid lines*), with *dashed curves* indicating the movements of thumb, wrist, and elbow during the last 100 ms before release. **c** The speed profiles of the thumb during the same ten trials. The thumb accelerates at about 50 m/s^2 to a speed of about 6 m/s. The dart is released (t=0, *vertical dashed line*) just before peak speed is reached. **d** The vertical hand position for the same trials. The dart is released just before the hand reaches the zenith of its movement path

such as release speed. We will neglect constant errors and limit our analysis to the variable error, which (in contrast with some other studies on throwing) is expressed by standard deviations throughout the paper. As a subject might change strategy in the course of an experiment, the variable error is not a measure of imprecision. We will use the word *precise* for being close to the planned value (which might be different from the mean value).

Dart throwing movements last too short a time (<150 ms) to be adjusted on the basis of proprioceptive information (Cordo et al. 1994) and do not require synchronisation with external events. Thus timing precision might be limited by the variability of the interspike intervals resulting from a constant input to the motoneurones of muscles involved (Calvin and Stevens 1968). Behavioural experiments that involved tapping (Wing and Kristofferson 1973) and ball throwing (Becker et al. 1990; Hore et al. 1995) suggest that precision in timing is rather limited; the reported average values for the standard deviations in timing range from 3 to 5 ms.

Sensitivity analyses of idealised (Calvin 1983) and simulated (Chowdhary and Challis 1999) throwing movements suggest that a timing precision of about 1 ms is needed to achieve normal human performance. Given the considerably larger actual variability in timing mentioned in the previous paragraph, the question arises as to how people can throw as precisely as they do. This question is the focus of the present study, in which we analyse the throwing behaviour of four subjects. Two hypotheses have been considered. The first hypothesis is that the trajectories assumed in the sensitivity analyses (Calvin 1983; Chowdhary and Challis 1999) are incorrect. Subjects might move their hand in a manner that keeps the combination of position, speed and direction of motion appropriate for reaching the target for more than a single instant, thereby reducing the required timing precision (Müller and Loosch 1999). We have not only determined the required timing precision of actual throws, but have also investigated which movement strategies lead to such a low required timing precision by studying idealised trajectories of the hand. The second hypothesis we have considered is that the variability in timing (as measured experimentally) is not due to lack of precision, but is the result of variability in the hand's trajectory.

Materials and methods

Subjects

Four right-handed adult male members of our laboratory (including two of the authors) volunteered as subjects in this study after giving informed consent. We refer to the subjects as S1–S4, according to their self-reported experience with playing darts. This ranged from "a few times a month" (S1) to "a few times in my life" (S4). Each subject made 120 dart throws at a dartboard positioned according to the rules of the World Darts Federation. The horizontal distance between the front of the board and any part of the shoes was at least 2.37 m, and the centre of the board (the bull) was 1.73 m above the floor. Within these constraints, the subjects were free to choose their posture when throwing. They chose to orient their trunk parallel to the throwing direction with their right foot in front. In contrast with normal dart practice, they were asked always to aim at the bull. The dart's final position on the dartboard was measured using a custom grid consisting of twelve radial sectors and twelve 1.25-cm-wide rings. The research in this study is part of an ongoing research program that has been approved by the local ethics committee.

Apparatus

To determine the time of release, a flexible metal cloth was fitted around the tips of the digits and connected via a resistance to a battery. This cloth was very light (about 0.1 g) and flexible; and its only effect (as reported by the subjects) was a reduced tactile sense. When both digits contact the dart, an electrical contact is made, so that the potential difference between the digits is zero. When the hand is opened, the potential difference between the digits increases to the voltage of the battery (with a time constant of about 50 ms). This potential difference and the trajectories of markers at the thumb, wrist, elbow and shoulder were measured at 250 Hz using an Optotrak movement registration system (Northern Digital, Waterloo, Canada). Only the movement of the thumb marker was analysed quantitatively.

Data processing

Although we sampled the data at 250 Hz, we were able to determine the various movement parameters at an interval of 1 ms. We fitted a straight line to the first three samples of gradual change in the potential difference between the digits after releasing the dart. The intersection of this line with the zero voltage line gave us the time of release with a precision of better than 1 ms. We determined the value of the thumb's kinematic parameters at this instant (which is generally not a sample point) by the following procedure. We first selected the seven measured position samples that were closest to the time of release (a time window of 24 ms). We then fitted a second-order polynomial to these position data, with the time of release declared as time zero. The three parameters of the fitted polynomial are our estimate of the thumb's position, speed, and acceleration at the time of release. This is a convenient method for combining data smoothing, interpolation, and differentiation in a single procedure. By shifting time zero by 1 ms, we could determine the kinematic parameters at that instant. By defining other instants (e.g. time of peak velocity) as time zero, and always selecting the seven measured position samples that were closest to that instant, we determined the kinematic parameters at those other instants.

Sensitivity analysis

Our predictions for the vertical positions of the dart on the board (used in the sensitivity analysis) are based on several assumptions. We assume that the dart moves exactly as the thumb does at the time of release, with coordinates (y_1, z_1) relative to the centre of the dartboard, speed v, and direction of motion φ (relative to horizontal). We assume that after the release the dart follows the parabolic trajectory of a point mass in vacuum, i.e. we neglect all rotations and air resistance. In that case, the flight time FT of the dart is determined by the horizontal component of the velocity $v\cos(\varphi)$and the distance z_1:

$$FT = \frac{z_1}{v\cos(\varphi)} \tag{1}$$

The vertical position of the dart on the board is determined by this flight time in combination with the vertical component of the speed and gravity:

$$y = y_1 + v\sin(\varphi)FT - \frac{9.8}{2}FT^2 \tag{2}$$

The dart's behaviour will of course not exactly follow these assumptions: air resistance will reduce its horizontal speed and its vertical fall. Due to the fins, the latter aspect will have a stronger impact on the dart's behaviour. Furthermore, as also a single digit can exert a force on the dart, it is likely that the exerted force is not zero at the time the electrical contact is broken, so that the dart moves faster (and falls less) than predicted. Both factors will lead to a predicted position of the dart that is systematically too low. Compared with the actual positions of the dart on the board, we indeed predict a position of the dart that is systematically 20 cm too low. As these predictions are only used to determine the sensitivity of the movement strategy for variations in movement parameters, it is more important for our analysis to know whether we could predict the differences between trials. The predictions correlated reasonably well with the actual final positions of the dart (correlation coefficients ranging from 0.6 to 0.9 for the four subjects). The spatial variability on the board that could not be predicted from our measures at release was about 3 cm, irrespective of subject and direction.

Equation 2 was used to determine two sensitivity measures: the *timing sensitivity* and the *speed sensitivity*. These measures were determined for the experimentally recorded throws, as well as for several theoretical movement strategies. We determine the *timing sensitivity* of the experimentally recorded throws by taking the difference between the predicted final position based on the measured values of φ, v, y_1 and z_1 at the actual time of release, and the predicted position based on the values 1 ms after release. We determine the *speed sensitivity* of the experimentally recorded throws by calculating the change in predicted final position (in centimetres) that would be caused by a 1-cm/s lower speed v.

The hypothetical movement strategy used in our sensitivity analysis is a circular hand-path. We again only regard the movement in the vertical plane. We assume that the thumb moves along a circular path (radius r) centred at (y_0, z_0). If we define the time the thumb reaches its zenith as t=0, the thumb's position (y_1, z_1) at any time t (relative to the time it reaches the zenith) is given by:

$$z_1 = z_0 - r\sin(vt/r) \text{ and } y_1 = y_0 + r\cos(vt/r) \tag{3}$$

Substituting these values in Eq. 1 and 2 yields for the vertical position of the dart on the board:

$$y = y_0 + r\cos(vt/r) + v\sin(-vt/r)FT - 4.9FT^2 \text{ with } FT = \frac{z_0 - r\sin(vt/r)}{v\cos(vt/r)} \tag{4}$$

The values for the sensitivity of the final dart position of hypothetical throws for variations in speed and time of release are obtained by taking the derivative of Eq. 4 to that variable.

Determining timing precision

We will use two methods to determine the precision of release timing. A straightforward method that has been used to estimate the precision of the timing of release is to determine the variability of the moment of release relative to other landmarks of the movement (Becker et al. 1990; Hore et al. 1995). The underlying assumption is that this variability arises solely from variations in the timing of the release. In other words, one assumes that the ideal moment of release is at a fixed time relative to the landmark, which only holds if other aspects of the movement of the arm are not variable.

Another way to estimate the timing precision is based on the above-mentioned sensitivity analysis. The underlying assumption is that timing variability limits performance. Calvin (1983) did this. He calculated the variability in release time that would give a specified variability in hit position, assuming that the hand rotates at a constant speed around the elbow (radius of curvature of 0.4 m). We will use a similar analysis for our experimental throws. However, our subjects clearly threw differently than the hypothetical throws that Calvin (1983) analysed. Our subjects' hands were usually still accelerating when they released the dart (Fig. 1c), and the hands followed less curved paths (radius of curvature between 0.5 m and 0.7 m). To determine whether these differences are important, we also analysed the timing sensitivity of theoretical hand trajectories.

Results

Our subjects' throws can be characterised in the following way (we give the range of the individual averages). They accelerated their hand up to a peak speed of 5.8–6.7 m/s. The dart was released about 2–11 ms before peak speed, about 4–25 ms before the hand reached its zenith. The local radius of curvature (in the vertical plane) at that time was 0.5–0.7 m. There was no systematic curvature in the horizontal plane. All subjects released the dart every trial at more or less the same position. At the time of release, the standard deviation in the hand's position in the vertical direction was between 1.4 cm and 3.3 cm, and in the lateral direction between 1.3 and 2.0 cm.

Before analysing the trajectories of the hand in more detail, we determined the distribution of the hits on the dartboard (Fig. 2). The standard deviation in the vertical position of the dart on the board varied between 2.9 cm and 6.1 cm across subjects (average 4.3 cm). This was not different from the standard deviation in the horizontal direction (range 2.7–6.1 cm; average 4.7 cm). The subjects' standard deviations on the board were inversely related with their experience (S1 performed best). Both the means (constant error) and the standard deviations were smaller (although not significantly so) in the sec-

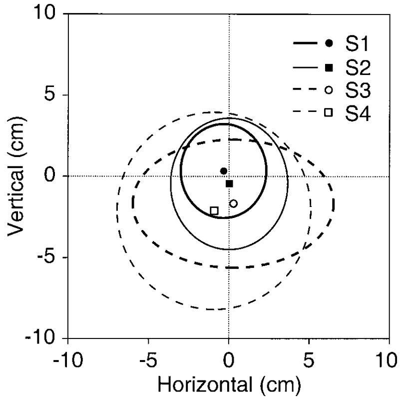

Fig. 2 Distributions of the throws on the dartboard for each subject. The *symbols* indicate the average position. The *major and minor axes of the ellipses* are the horizontal and vertical standard deviations

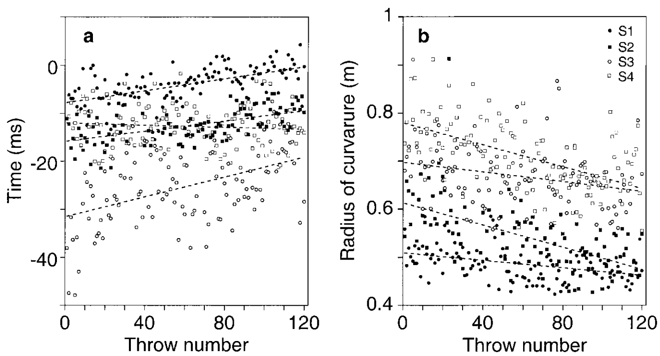

Fig. 3a, b Development of two parameters for consecutive throws. The *dashed lines* indicate the best fitting linear regressions for each subject. **a** The time of release (relative to the time the hand reaches the zenith of its path). **b** The radius of curvature of the hand's path

ond half than in the first half of the experiment. As a result, the average distance from the bull reduced from 6.0 cm to 5.4 cm in the course of a session.

To see whether the decrease in variability during the course of a session was due to a change in movement strategy, we investigated whether the various movement parameters varied systematically with trial number. Two of them did. We plotted these as a function of the trial number in Fig. 3. All but our least experienced subject S4 showed a significant (5–10 ms) delay in the time of release during the session (Fig. 3a). The radius of curvature (in the vertical plane) was smaller for the better subjects, and decreased for all subjects during the course of the experiment (Fig. 3b). Both changes in the movement parameters (later release and smaller radius of curvature) are in the direction of the movement strategy of the better subjects. Therefore Fig. 3 suggests that good performance correlates with a small radius of curvature and a release close to the zenith of the hand's path.

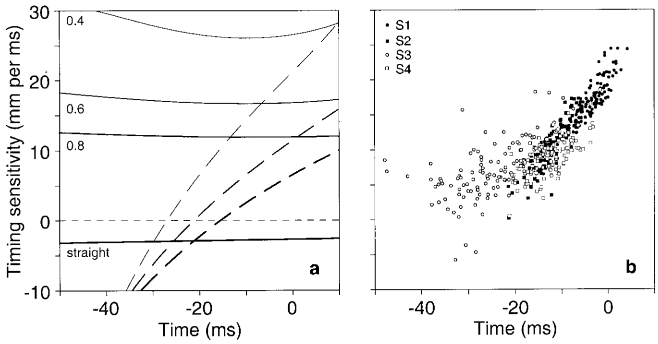

Fig. 4a, b Timing sensitivity: how many millimetres lower a dart would hit the board if it were released 1 ms later, as a function of the time of release (relative to the time the hand reaches its zenith). A positive value for the sensitivity means that the dart ends lower if it is released later; a negative value that it ends higher. **a** The timing sensitivity of hypothetical trajectories with a constant curvature (radii in metres indicated in the graph). *Continuous curves* Constant hand speed (6.5 m/s); *dashed curves* the hand accelerates in 140 ms to a speed of 6.5 m/s at the zenith. **b** The timing sensitivity of each throw in our experiment. The throws of the different subjects are represented by different symbols. The best subject (*S1*) released the darts near the zenith, at a time of high timing sensitivity

Timing sensitivity

We analysed the timing sensitivity of both theoretical and actual throws. The results of the analysis of the timing sensitivity of circular hand trajectories (the derivative of Eq. 4 with respect to time) are given in Fig. 4a. The continuous curves show the timing sensitivity for hypothetical constant speed paths as a function of the time of release (relative to the time the hand reaches its zenith). They indicate that reducing the radius of curvature (a strategy correlated with good performance) increases the sensitivity for timing errors.

To check whether the experimentally observed acceleration of the hand at the time of release (Fig. 1c) changes the sensitivity for timing errors, we used our subjects' average acceleration instead of a constant velocity in a second set of model calculations (substitute v with v_0+at in Eq. 4). The dashed curves in Fig. 4a show that a smaller radius of curvature makes the trajectory still more sensitive for timing errors, but that the accelerating hand makes the timing sensitivity time-dependent. For the accelerating hand, the timing sensitivity depends strongly on when in the path the dart is released. Timing errors have a negligible effect for darts released about 20 ms before the zenith of the curve. Thus, at this time, our theoretical thrower has a combination of path and acceleration that makes the outcome almost insensitive for variations in the moment of release (the throwing strategy proposed by Müller and Loosch 1999). However, Fig. 3a has already shown that the better subjects (S1–S2) released the dart considerably later.

Our analysis of our hypothetical throws indicates that timing sensitivity can be reduced by using a large radius of curvature and releasing the dart relatively early

(Fig. 4a). Our subjects do not seem to use this strategy (Fig. 3). Perhaps our subjects' trajectories are not well approximated by these hypothetical throws. We therefore calculated the timing sensitivity for each experimental individual throw. We thus determined how much the final position of the dart on the board would have changed if the dart had been released 1 ms later than it was actually released. The results are plotted in Fig. 4b as a function of the time of release (relative to the moment the hand reaches its zenith). The timing sensitivity of the throws in our experiment depended on the time of release in about the same manner as it did for our hypothetical accelerating throws (dashed curves in Fig. 4a). In particular, the timing sensitivity was smaller when the dart was released longer before the hand reaches its zenith. Apparently, however, our subjects did not take advantage of this possibility. As a result, the average timing sensitivity was 11 mm positional error per millisecond timing error (range 7–17 mm/ms), and was larger for the better subjects.

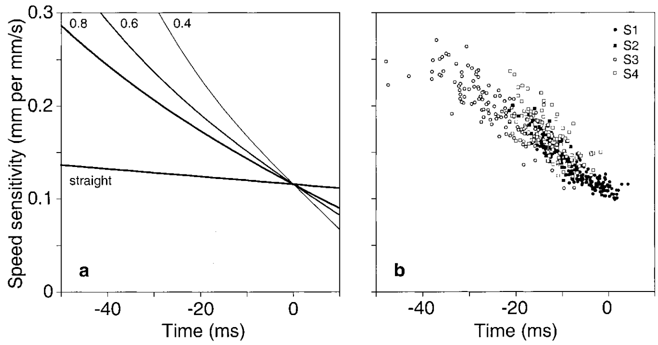

Fig. 5a, b Speed sensitivity: how many millimetres lower a dart would hit the board if it were released at a 1-mm/s lower speed. **a** The speed sensitivity of hypothetical trajectories with a constant curvature (radii in metres indicated in the graph) and the dart moving at 6.5 m/s at release. These predictions are independent of acceleration. **b** The speed sensitivity of each throw in our experiment. The throws of the different subjects are represented by different symbols. Note that the best subject (*S1*) released the dart at a time of low speed sensitivity

Timing precision

Our first estimate of the precision of our subjects' timing is obtained by dividing the vertical variability of the hits on the dartboard (Fig. 2) by the average timing sensitivity. For S1, the darts' vertical positions on the dartboard had a standard deviation of 29 mm. Considering his average timing sensitivity of 17 mm/ms (Fig. 4b), this subject must have a timing precision that is better than 1.8 ms. Similarly, we can estimate the timing precision of our worst subject S4 to be better than 6.9 ms. These values are an upper estimate of the precision, because this sensitivity analysis neglects all other sources of spatial variability, such as the dart's speed and direction of motion at release.

We can obtain a second estimate of the precision of the timing of release by determining the variability in the moment of release relative to other landmarks of the movement. The release of the dart was on average 13.5 ms before the zenith of the hand's trajectory (Fig. 1d). The standard deviation of this interval ranged between 3.4 and 7.7 ms (not correlated with performance) for the four subjects. The variability in release timing was similar (2.6–6.7 ms) relative to a second landmark: the peak speed (cf. Fig. 1c, d; see also Hore et al. 1995). For our best subject, both landmarks yielded a variability of 3.8 ms, which is considerably larger than the 1.8 ms that we estimated as an upper limit using the sensitivity analysis. The explanation for this apparent conflict is that the requirement of having a stable landmark is not fulfilled. The variability in the timing between the two landmarks (peak speed and the zenith of the path) ranged from 1.4 to 8.8 ms for the four subjects. This variability between the landmarks implies that the ideal moment of release relative to one of them cannot be the same for each movement. This means that not all variability in the measured timing of release relative to a landmark can be attributed to imprecision in timing.

All these findings indicate that reducing timing sensitivity is not part of the strategy for improving performance. This suggests that timing precision is not the factor that limits precision when throwing darts. If so, what determines precision? We could get a hint by performing a sensitivity analysis for imprecision in parameters of the hand's trajectory, rather than imprecision of timing. The sensitivity for a positional error parallel to the board is not very informative: 1 mm positional error of the hand yields an error of 1 mm on the board, independent of the time of release. The sensitivity to errors in speed is more interesting. Figure 5a shows that the speed sensitivity for a circular hand movement depends on the time of release, but in the opposite way to the timing sensitivity. The later the dart is released, the less influence an imprecise speed has, and, again, the sensitivity of our subjects' throws follows the model analysis (Fig. 5b). The reduction of the effect of speed errors could therefore be a good reason to release the dart later. This argues in favour of speed precision being a limiting factor in dart throwing, rather than timing precision. A sensitivity analysis of parameters describing the path (such as the radius of curvature and the direction of motion) is not straightforward. One reason for this is that we express the timing of our throws relative to the zenith. When examining the effects of imprecision in the path, this point is no longer well defined. We therefore did not attempt such an analysis. We will discuss the effect of angular errors in the next section.

Discussion

This paper provides several arguments for our claim that subjects can time the release of the dart very precisely, so that the precision of the timing of release is not a limiting factor in dart throwing. Releasing the dart late (close before the zenith of the curve) and moving the hand along a curved path both increase the sensitivity for timing imprecision (Fig. 4). Nevertheless, the more experienced subjects released the darts later and moved along a more curved path than the less experienced subjects. Moreover, at the end of the session our subjects released the dart about 6 ms later, and with a more curved path than in the first trials of a session (Fig. 3). This resulted in a slight (but not significant) decrease in spatial variability. These results indicate that practice leads to a strategy that is highly sensitive for timing errors, and thus imposes a high constraint on timing precision. This choice of strategy is very unlikely if timing imprecision is the limiting factor for good performance.

We concentrated on the vertical variability, because our aim was to understand the contribution of timing imprecision. For the horizontal component of the movement, the timing sensitivity is very close to zero, because the horizontal component of the hand's path is almost straight. Imprecise timing will thus only affect the vertical component of the dart's movement. If timing were imprecise, we would therefore expect much more variability in the vertical than in the horizontal position of the dart on the board. Figure 2 shows that the standard deviation in the vertical position of the dart on the board was not larger than that in the horizontal direction. This confirms that the imprecision in release timing is not an important source of throwing imprecision; other factors must be the main cause of the variability of dart throws.

Figure 5 argues in favour of a strategy in which subjects reduce the sensitivity to errors in the speed. This suggests that the precision of speed might be the limiting factor in dart throwing. Such a suggestion fits nicely with a recent theory on movement planning, which assumes that all neural variability is in the intensity (and not in the timing) of neural output (Harris and Wolpert 1998). The hypothesis that speed imprecision is the main cause of throwing imprecision, however, cannot explain why the variability in final positions of the dart is just as large in the horizontal as in the vertical direction, because the final horizontal position of the dart is independent of the speed of the throw.

For one parameter of the hand's trajectory (the direction of motion at release), errors have equal effects on the horizontal and vertical component of the dart's final position. This suggests that imprecision in the direction of motion at release might be the main cause of throwing imprecision. We discussed at the end of "Results" why we could not perform a sensitivity analysis for this parameter. The speed and direction of motion at the time of release are highly correlated in throwing ($r^2>0.25$ in our study; see also Dupuy et al. 2000; Kudo et al. 2000), which explains why the sensitivity analyses we performed pointed in the direction of speed as the limiting factor. Additional support for the direction of motion as a limiting factor can be found in several other studies on throwing. For underarm throwing to a horizontal target, Dupuy et al. (2000) showed that subjects choose a combination of speed and direction of motion at release that minimises the sensitivity of the throwing distance to directional imprecision. For overarm throwing to a vertical target, Hore et al. (1996) showed that angular variability is the main source of throwing imprecision. They claimed that this angular variability was due to limitations in the control of timing. Our results show that the opposite is more likely: that the observed timing variability is due to variations in the hand's trajectory.

The final outcome of the sensitivity analysis was that timing precision can be better than 1.8 ms. How much better depends on the amount of variability that is present in other movement parameters. One cannot combine such contributions to the final variability on the board and attribute the unexplained variability to timing imprecision, because a simple analysis of our data shows that the various parameters describing the hand's movement at release are not independent. If they were independent, one would expect a strong correlation of the final dart position with the position of the hand at release. We calculated this correlation for both the horizontal and vertical movement components of our four subjects' throws. Five of the eight combinations did not even show a weak correlation. A similar result has been reported for ball throwing (Hore et al. 1996; Martin et al. 2001). Such results are closer to the other extreme, whereby variations in the hand's position are completely compensated for by variations in other release parameters.

What mechanism causes this compensation? As noted in the "Introduction", dart throws are too fast for corrections based on afferent information. If corrections are the basis of the compensation, they thus have to be based on efferent information combined with internal forward models of throwing (Wolpert et al. 1998; Hore et al. 1999). Alternatively, the compensation can also be completely pre-planned. Subjects might choose a different throw from the infinite number of possible combinations of trajectories and timing that result in the same final position of the dart for each trial. This is equivalent to the "redundancy problem", whereby many joint configurations lead to the same value of the task variable (e.g. Gielen et al. 1997; Scholz et al. 2000). We indeed found that the variability in timing between landmarks is as large as between a landmark and release, which explains the apparent imprecision in release timing reported in previous studies (Becker et al. 1990; Hore et al. 1995). Thus the variability found in the release parameters is not only due to imprecision, but is partly caused by variability in the hand's intended trajectory.

We show that subjects do not move their hand along a trajectory that reduces the required timing precision. Further analysis of their throws suggests that the limiting factor for dart throwing is not the timing of release, but the variability in the hand's trajectory (position, speed and direction of motion). We argue that the variability in movement parameters (including the timing of release) is much higher than the precision with which these parameters are regulated, because part of the variability in a given parameter can be caused by (a compensation for) the variability in another parameter.

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