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Timing the moment of impact in fast human movements

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ABSTRACT

The reported resolution of timing the moment of impact in fast human movements differs widely depending on the task. Surprisingly, better timing is reported for the demanding task of batting a ball than for the much simpler task of tapping in synchrony with two hands. We wondered whether this is because a sizeable part of timing variability arises from misjudging the distance in the direction of one's own movement, so that moving faster (as the bat does when moving toward a ball) improves timing. We found that moving faster does indeed improve timing in both the above-mentioned tasks. After removing the proposed contribution of misjudging the distance in the direction of one's own movement, we estimated that the remaining standard deviation in timing is just over 6 ms for both tasks.

1. Introduction

Timing is a fundamental aspect of human actions. Rhythmic tapping has often been used to examine how accurately and precisely movements can be made (e.g. Ivry & Hazeltine, 1995; Wing & Kristofferson, 1973). A large part of this extensive line of research is concerned with how well people can perform and maintain certain rhythms (for a review see Repp, 2005). In order to tap in rhythm, people both have to judge the intervals correctly and to produce movements that give rise to impacts at the appropriate moments. From tapping studies we know that the variability in the timing of tapped rhythms is larger when the lengths of the intervals are longer. This is mainly because the precision with which one can judge the interval increases with the length of the interval (Doumas & Wing, 2007).

The ability to reproduce rhythms has obvious relevance for activities such as making music, but we are more interested in what the studies on rhythmic tapping can tell us about the precision of the motor processes involved in producing the individual movements. For this, one can best consider the task of tapping a simple rhythm synchronously with the left and right index fingers (Doumas & Wing, 2007; Doumas, Wing, & Wood, 2008). Assuming that a single judgment is made about the appropriate moment to tap, and that this results in simultaneous commands being sent to both fingers, corrections to the rhythm will occur before the signals to the two fingers diverge so that any lack of synchrony can be attributed to variability in executing the movements, and the relative timing of the two digits provides a direct estimate of the digits' combined temporal movement precision (Vorberg & Hambuch, 1984). In simple synchronous tapping tasks, the variability in the relative timing of when the two fingers hit the surface is about 14 ms (data for equal amplitude movements in Fig. 6 of Doumas et al., 2008), which corresponds with a precision in making each tapping movement of about 10 ms (assuming that the two fingers have independent and equal variability, we divide the value by $\sqrt{2}$ to get a value for each finger).

There is reason to doubt that the precision of 10 ms can be generalised to other movements than tapping with the fingers, because a considerably higher precision has been reported for performance in sports in which timing is critical (McLeod & Jenkins, 1991; Regan, 1992). Anecdotal reports about exceptional performance, such as the estimated 2–3 ms resolution of interception by top cricketers (Regan, 1997), may be misleading because they only tell you how well the best players did on the occasions at which they did exceptionally well. McLeod, McLaughlin, and Nimmo-Smith (1985) asked normal subjects to hit a falling ball with a bat. Their subjects hit about 66% of the balls within a 10 ms time window and about 88%

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of the balls within a 20 ms time window, which corresponds to a standard deviation in timing of about 6 ms (for the values reported in McLeod & Jenkins, 1991, the standard deviation would be about 7 ms). This standard deviation combines uncertainty about when the target should be hit with variability in getting there at that time. As the synchrony between the fingers in synchronous tapping isolates the latter source of variability, we expect a larger standard deviation in timing for interception than for the synchrony between the fingers in synchronous tapping. However intercepting moving targets seems to be more precise. How can this be?

We examine the possibility that intercepting moving targets is more precise than synchronous tapping because the swinging bat moves much faster than the tapping fingers. To explain why the speed of the movement may matter, we first consider why temporal precision is limited. The timing precision that we are concerned with is the timing at the moment of interest: when the bat hits the ball or when the fingers hit the surface. When hitting a ball with a bat, it takes time for visual information that reaches our eyes to be transformed into muscle contractions, and for muscle contractions to bring the bat to the appropriate place, so timing the hit requires prediction. The timing precision will therefore depend on how well one can predict the moment of interest at the last moment at which the timing can still be adjusted (Brenner & Smeets, 2011a).

The brain needs to judge when the ball will be at a certain place, or where it will be at a certain time, so limitations in the resolution of visual judgments will give rise to some variability. Variability will also arise if the commands change for other reasons (Brenner & Smeets, 2011b; van Beers, 2009) or if the muscles respond slightly differently to the same commands on different occasions (Harris & Wolpert, 1998). Moreover, even if exactly the same commands give rise to exactly the same muscle contractions on each attempt, the outcome will not necessarily always be the same, because the distance that needs to be moved depends on exactly where the ball falls and exactly where the batsman is standing. The brain may adjust the commands on the basis of the estimated distance that the bat needs to be moved, but if so misjudging the distance will lead to variability in timing.

As already mentioned, for tapping a prescribed rhythm synchronously with two fingers, the variability in judging when the next taps should occur on the basis of preceding sensory information is relevant for reproducing the rhythm itself, but not for the synchrony between the fingers. Besides depending on how the muscles respond to motor commands and on adjusting such commands in response to errors, precision may also depend on the extent to which the subject misjudges the height of the finger above the surface while moving towards it. That may explain why the variability in timing between the fingers is larger when the amplitudes of the fingers' movements are different (Doumas et al., 2008): misjudging the position of the surface will introduce errors in synchrony if the digits that move towards the surface from different heights move at different velocities.

We here consider the possibility that variability in estimating the distance that needs to be moved is a substantial source of variability in timing. If one finger hits the surface before the other when attempting to tap synchronously with both fingers, this could be because the first finger moved sooner or faster than intended, but it could also be that it was closer to the surface than anticipated so that it hit it earlier than expected. Similarly, misjudging the distance between the bat and the ball's trajectory will give rise to a timing error, because the bat will not have moved far enough or will have moved too far at the anticipated moment of contact. The faster the finger or the relevant part of the bat moves, the smaller the timing error that arises from such a spatial misjudgment will be, because the same distance is covered in less time (Brouwer, Brenner, & Smeets, 2000; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). If we assume that this is the only reason for timing being more precise for faster movements, we can determine whether misjudging the distance that is to be moved has a substantial influence on timing precision by comparing movements with different speeds. If misjudging the distance that is to be moved is not a negligible factor, we expect to see better timing for faster hits.

Of course, the tapping finger moves much more slowly than the hitting bat. However, this does not automatically mean that timing precision should be lower (following the reasoning of the previous paragraph), because the distance that is to be moved is presumably judged more accurately when tapping than when batting since the distance is smaller. By comparing fast and slow movements (batting towards *far* and *near* targets; *loud* and *quiet* synchronous tapping), we can estimate how misjudging the distance that is to be moved contributes to the timing precision in each task. This will reveal whether misjudging the distance that is to be moved is a negligible factor. We can then compare the timing precision that remains after correcting for errors in judging the distance that is to be moved. After such correction we expect precision to be better for tapping, because the precision of the tapping task only depends on the precision of movement execution (because misjudging the appropriate moment will influence both fingers to the same extent so it will not affect their synchrony) whereas the precision in the hitting task also depends on how well one judges when the ball will arrive at the point of interception.

2. Methods

2.1. Equipment, procedure and analysis for the hitting task

Ten male students (none of whom played baseball) each attempted to hit 144 falling tennis balls (6.6 cm diameter) with a children's foam-covered baseball bat that we bought in a toy shop (total length: 68.5 cm; diameter of relevant section: 5 cm). The balls were dropped from a height of 5.7 m in a large well-illuminated hall. The first 10 cm of the balls' motion was through an 8 cm diameter cylindrical tube, so that the standard deviation of the position of the ball at the height at which it was hit was only 2.2 cm (in the direction of the bat's motion). The ball was hit at a height of 124 ± 20 cm from the floor (mean $\pm$ standard deviation). At the time it was moving downwards at 8.7 m/s. The position of the tip of the bat was recorded at 800 Hz with an Optotrak 3020 system (Northern Digital Inc., Waterloo, Ontario, Canada).

Each subject hit 72 balls towards each of two 90 by 90 cm targets (Fig. 1). One target was facing the subject at a distance of 4.5 m. This position was chosen to encourage subjects to hit the ball hard. The other target was on the floor at a distance of 2.5 m. This position was expected to encourage subjects to hit the ball gently. Half the subjects started with the near target and the others with the far target. The first twelve balls that were to be hit towards each target were considered practice trials. For the remaining 60 balls we determined whether the ball had been hit and the speed of the relevant part of the bat just before the hit or miss. For balls that were hit, we also determined the acceleration of the bat as a result of the hit. For each subject and target we used these values to determine the fraction of balls that were hit, the average direction of impact between the bat and the ball, and the average speed of the relevant part of the bat just before the hit.

Whether the ball had been hit was scored during the experiment. This was converted into a fraction of balls that were hit by dividing the number of hit balls by the number of attempts (always 60). The speed of the relevant part of the bat just before a hit or miss was determined from the velocity of the tip of the bat and the centre of rotation. For hits, the velocity of the tip was estimated by dividing the bat's displacement during the last 2.5 ms before the moment of impact by the 2.5 ms difference in time. For misses we used the velocity during the last 2.5 ms before the bat crossed the average point at which balls were hit. The centre of rotation was determined from the

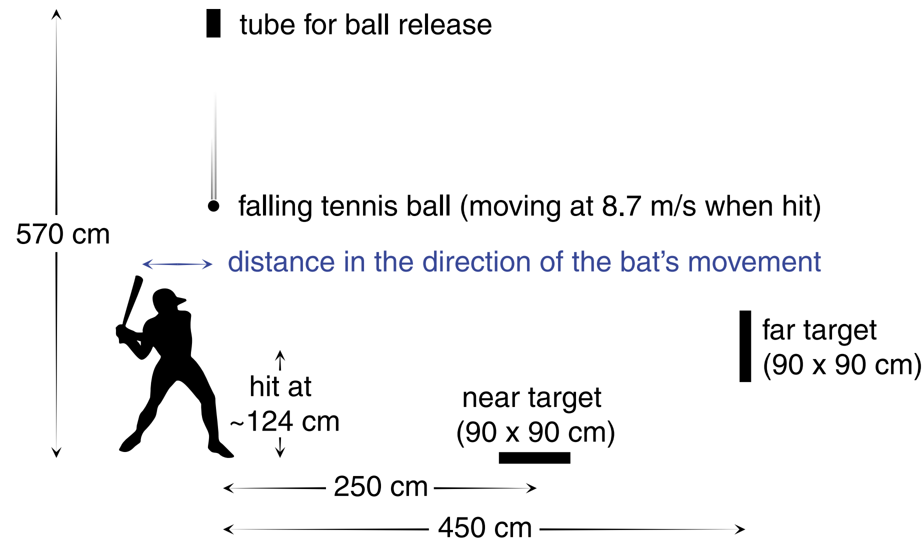

Fig. 1. In the hitting task, subjects hit a 6.6 cm diameter falling ball with a soft 5 cm diameter bat. We obtained fast and slow hits by asking them to aim for a far or a near target, respectively. The position of the tip of the bat was recorded at 800 Hz.

tip's position at the moment of impact (or, for misses, when it crossed the average point at which balls were hit), and its positions 100 ms earlier and 100 ms later. We determined the radius of the circle that passes through the projection of these three positions on a horizontal plane. This radius is an estimate of a virtual rotation point for the combination of arm and bat. The speed of the relevant part of the bat just before a hit or miss was estimated by combining the estimated velocity of the tip of the bat with the assumption that the ball was hit 20 cm from its tip and that the virtual rotation point is along an extension of the main axis of the bat. When we report the estimated average speed of the relevant part of the bat it is always the horizontal speed just before the hit. The vertical component of the bat's motion was considered by subtracting it from the ball's velocity so that we could consider the bat and the ball to be moving orthogonally to each other.

For balls that had been hit, the moment of the hit was determined on the basis of the acceleration of the tip of the bat when it hit the ball. Acceleration was determined by subtracting the distance between the previous position and the current position from the distance between the current position and the next one, and correcting for the time between two measurements (1.25 ms). This was done separately for each direction. Impact with the ball can be seen as a peak in the combined acceleration during the swing. The first moment at which a change towards the peak was visible was considered to be the moment of impact.

Subjects could hit as they pleased, but they had to try to hit the ball towards a specified target rather than just to hit the ball. Consequently, they had to consider the direction in which the ball was to be hit, so we could not just assume that they were aiming to reach the ball at the optimal time for intercepting it. Trying to make the centres of the bat and ball arrive at the point at which their paths cross at the same time maximises the likelihood of the bat hitting the ball, but introduces a bias to hit balls upwards. Our subjects are therefore likely to aim to arrive later in order to hit the ball when it is lower so that they hit it further forwards. We estimated the extent to which they did so from the average direction of the acceleration of the bat at impact. The direction of impact was determined from the relative magnitudes of the sagittal and vertical accelerations at the moment that the combined acceleration as a result of impact with the ball reached its peak. Details of how the direction of impact is combined with the fraction of hit trials to estimate the timing precision and the time aimed for will be presented in the Results section.

2.2. Equipment, procedure and analysis for the tapping task

Six members of staff, including two of the authors, each tried to tap in synchrony with their two index fingers on two force sensors (ATI, Nano17 Ft). They did so in two, one-minute sessions. During the sessions, tones were presented at 2 Hz to indicate the approximate tapping rate, but subjects were explicitly informed that we considered it to be more important that the fingers tapped in synchrony than that the taps would be in synchrony with the tone. Subjects were instructed to tap with their fingernails in order to get a sharper impact. The only difference between the two sessions was that in one session they were asked to tap softly and in the other to tap loudly. A louder tap is obviously achieved by moving faster at the moment of impact. Three subjects did the soft taps first and the others did the loud taps first. Subjects were sitting comfortably in front of the force sensors that were 10 cm apart on a table in front of them. They were encouraged to rest their wrists on the table for stability. They were allowed to look at their fingers, so they could judge the distance that their fingers had to move visually as well as from a combination of haptics and memory.

The positions of the nails of the subjects' fingers were measured at 800 Hz with the Optotrak 3020 system. The force on the sensors was measured at 2000 Hz with the Optotrak Data Acquisition Unit. We used the positions to determine the speeds of the fingers when they were between 5 mm and 1 mm above the surface of the force sensor. For each trial and finger we determined the first and last measurement that was within this range and divided the displacement between them by the time interval between them. The moment of the tap was determined from a combination of the deceleration of the finger and the force on the sensor. Tapping the sensor with the nail of the finger gave a sharp deceleration of the finger as well as a sudden increase in force rate. Both were easy to detect (Fig. 2). For each finger, we used the average of the times estimated from the deceleration and from the force rate as our measure of the time of the tap. We used the latter to determine the standard deviation in the time difference between the tap of the left and the right index finger. Since this standard deviation combines timing errors of the fingers of both hands, we divided the outcome by $\sqrt{2}$, assuming that the timing precision

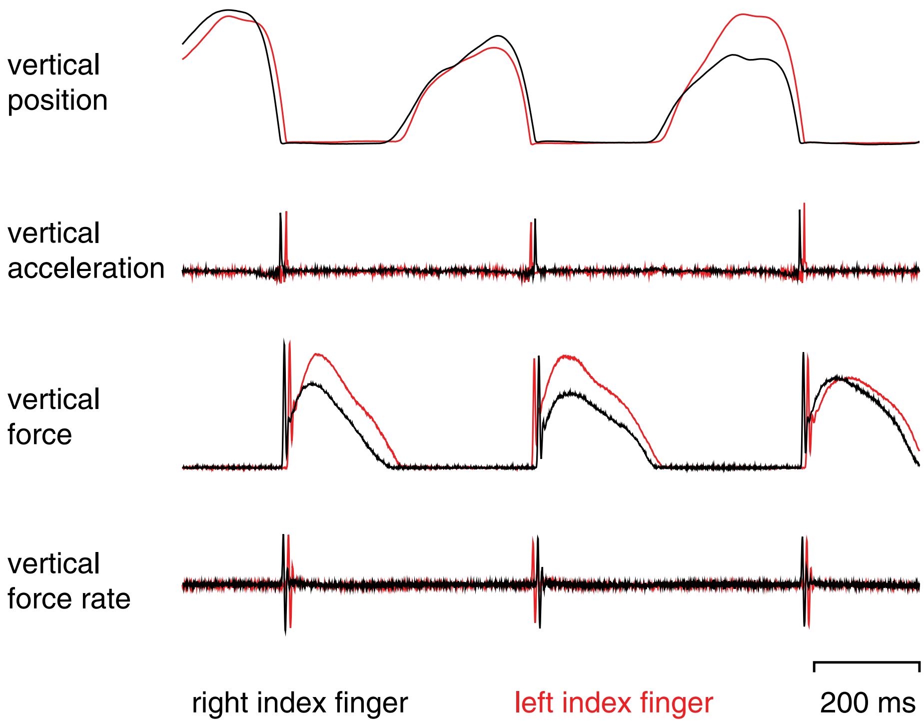

Fig. 2. Example of measurements of the vertical position and force of the left (red) and right (black) fingertip during three consecutive taps in the synchronous tapping task. We used the average of the moments at which vertical acceleration and vertical force rate started to increase as the moment of the tap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is the same for both hands (note that we must anyway assume that the variability in the two hands is independent, because that is how motor errors are distinguished from time-keeping errors in this task; Doumas et al., 2008).

2.3. Resolution of our equipment

As already mentioned, the positions of the tip of the bat and of the nails of the subjects' fingers were measured at 800 Hz, and the force on the force sensors was measured at 2000 Hz. We determined the spatial precision of the Optotrak system by measuring the standard deviation in measurements of the position of a static infra-red light emitting diode within the region in which the measurements were made. This was a similar diode to the ones that were attached to the tip of the bat and to the nails of the fingers to determine their positions during the experiments. The standard deviation in the measured coordinates was between 0.02 and 0.05 mm, depending on the direction in space in which the variability was measured. During the experiments, the Optotrak camera was placed so that the important measures would be determined with the highest resolution. Consequently, only the path curvature in the hitting task relied on measurements with the poorest resolution. The resolution of the force sensors was determined in a similar manner. We found a standard deviation in the relevant direction of about 0.01 N, both with no force on the sensor and with a 100 g object lying on the sensor.

2.4. Separating the contribution of misjudging the distance that is to be moved from that of other sources of timing variability

Both the tasks were designed to give us estimates of timing precision for two different movement speeds. If we assume that individual subjects' timing precision arises from a combination of independent variances in judging the distance that is to be moved ($\sigma^2_{\text{distance}}$) and in other sources of timing variability (σ^2_{timing}), and that neither of these variances depends on the speed of the movement, we can estimate the two sources of variability from the subjects' measured precision for the two movement speeds (σ_i). For each speed (V_i) we can write:

$$\sigma_i = \sqrt{\sigma^2_{\text{timing}} + \frac{\sigma^2_{\text{distance}}}{V_i^2}}$$

where σ_i is the standard deviation in timing that belongs to the speed V_i. Since we have two sets of values for σ_i and V_i for each subject, we can estimate the values of σ_{timing} and σ_{distance} for each subject on the basis of this equation. For the hitting task, V_i is the average speed of the relevant part of the bat just before it hits the ball and σ_i is the standard deviation in timing the hit, which we derived from the fraction of hit balls. For the tapping task V_i is the average speed of the fingers as they approach the surface and σ_i is the standard deviation in timing the tap, which we derived from the distribution of asynchronies between the fingers.

3. Results

3.1. Hitting a ball

The bat moved more slowly, the ball was hit further upwards and most subjects hit more balls when aiming for the near target (slow hits; Table 1). A higher fraction of hit balls when hitting slowly does not mean that the timing was better, because moving more slowly increases the time window for hitting the ball. To understand why, consider moving extremely slowly: the ball will always fall on the bat. Thus, the conversion from the fraction of hit balls to timing precision has to consider the speeds of the bat and ball. Another factor that needs to be considered is the timing that subjects were aiming for, because aiming for the moment that would give the highest fraction of hit balls is not optimal for propelling the ball towards the target.

Table 1
The fraction of balls that were hit, the average direction of impact and the estimated average speed of the relevant part of the bat for each target and subject. A direction of zero corresponds with hitting the ball horizontally and a direction of 90° corresponds with hitting it straight upwards.

Subject	Fraction hit		Average direction (deg)		Average speed of bat (m/s)	
	Fast hit	Slow hit	Fast hit	Slow hit	Fast hit	Slow hit
1	0.57	0.75	15.6	36.4	19.9	6.1
2	0.58	0.68	29.9	45.1	19.6	5.0
3	0.65	0.80	16.0	45.8	20.2	7.5
4	0.65	0.48	28.6	35.4	16.7	5.9
5	0.65	0.85	21.5	48.4	16.8	5.1
6	0.50	0.78	30.3	50.7	13.1	2.4
7	0.60	0.80	20.8	38.8	24.5	5.7
8	0.73	0.90	25.7	47.5	23.3	4.7
9	0.57	0.58	18.2	31.3	16.6	6.2
10	0.78	0.48	20.8	28.0	23.1	8.1

Again, to understand why, consider the ball falling on an extremely slowly moving bat: the ball will bounce upwards. One must arrive later than the moment that would give the highest fraction of hit balls to avoid hitting the ball too far upwards.

Fig. 3 illustrates how a fraction of hit balls and the associated average direction of the hit are combined to give a value for the precision in timing (standard deviation) and a value for the kind of impact that the subject was aiming for (how much later to try to hit the ball than would maximise the likelihood of hitting it). Both the fraction of the balls that will be hit (thin curves) and the average direction of impact (thick curves) depend on the timing that one is aiming for (values on horizontal axis) as well as on the timing precision (two possible values are represented by differently coloured sets of curves). For a standard deviation of 5.4 ms (black curves), both the fraction of hit balls and the average direction of impact correspond with the measured values (dashed horizontal lines) when aiming to arrive 2.5 ms after the moment that would give the highest number of hits (vertical line). For other standard deviations (the red curves show values for a standard deviation of 6.0 ms) the fraction of hits and the average direction do not match the measured values when aiming for the same time (see horizontal separation between arrows). For this subject and condition the precision in timing was therefore 5.4 ms and he was aiming to hit 2.5 ms after the moment that would lead to the largest fraction of touched balls. The relevant part of the bat was moving at 19.6 m/s (horizontal and vertical velocities of the tip of the bat of 25.8 and 6.7 m/s; centre of rotation 83 cm from the tip).

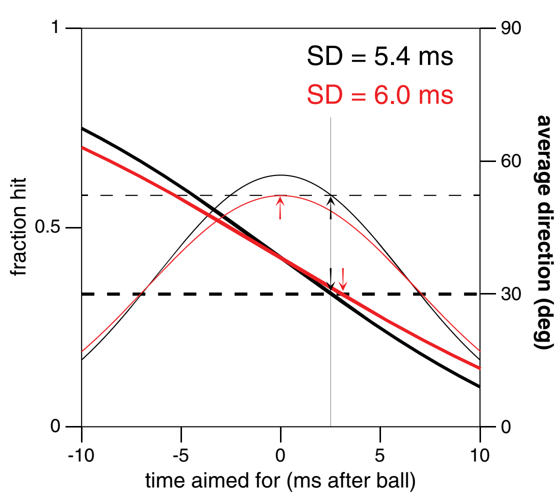

Fig. 3. Converting a fraction of hit balls and an associated average direction of impact into a standard deviation in timing and a time aimed for. The thin lines indicate the fraction of hit balls (left axis) for a given temporal precision (colour of curve) and time aimed for (horizontal axis). The thick lines indicate the direction of impact (right axis) for the same cases. The dashed horizontal lines indicate the measured values (for fast hits by subject 2). The red and black curves indicate predictions for standard deviations of 6.0 and 5.4 ms, respectively. The arrows indicate points on the curves that correspond with the measured values. The horizontal separation between the red arrows indicates that for this standard deviation the two measured values are not consistent with a single *time aimed for*. The measured values are only consistent with a single *time aimed for* (black arrows aligned horizontally, in this case at a value of 2.5 ms) for a standard deviation of 5.4 ms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

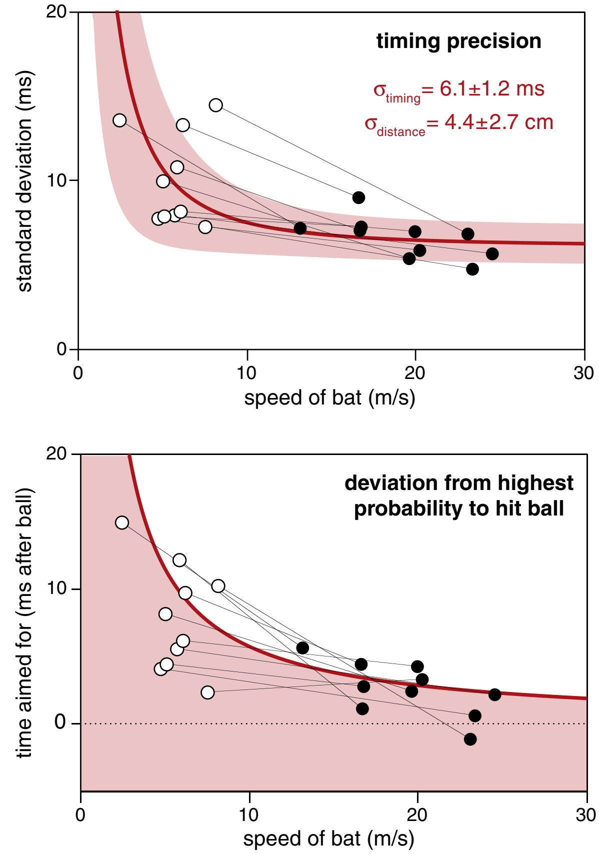

Fig. 4. Results of the hitting task: standard deviation in timing the hit and systematic deviation from hitting when the likelihood of making contact with the ball was maximal, both as a function of the estimated average speed at which the relevant part of the bat is moving when it hits the ball. Open symbols: slow hits. Solid symbols: fast hits. Lines connect the individual subjects' values. The red curve and shaded area in the upper panel shows what one would expect (mean ± one standard deviation) for the mentioned values of σ_{timing} and $\sigma_{distance}$. The red curve in the lower panel separates timing values for which the ball is hit upwards (shaded region) and downwards. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The upper panel of Fig. 4 confirms the idea that timing is more precise when the bat is moving faster just before impact. A comparison between the subjects' values for the two kinds of hits revealed that the standard deviation was significantly larger when hitting more slowly (paired *t*-test: $t_9 = 4.9$; $p = 0.001$). We used the equation presented in Section 2.4 to separate the standard deviation in timing into a part that we attribute to errors in judging the distance that is to be moved and a part that we attribute to other factors that limit timing precision. The calculated average value for the standard deviation in judging the distance ($\sigma_{distance}$) was 4.4 cm with a standard deviation across subjects of 2.7 cm. For the remaining aspects of timing (σ_{timing}) the value is 6.1 ms, with a standard deviation across subjects of 1.2 ms. The curve and shaded area in the top panel of Fig. 4 show how performance is expected to depend on hitting speed for these values. The results are consistent with the notion that misjudging the distance that is to be moved contributes substantially to the measured timing precision, at least when moving relatively slowly.

The lower panel of Fig. 4 shows that subjects did not simply aim for the moment that would make the bat touch a maximal number of balls, but aimed for the bat to arrive later so that the ball was not hit too far upwards too often. The curve shows how much later than the optimal time for maximising the number of touched balls subjects have to aim for in order to hit the ball horizontally (on average). Especially for slow hits, aiming for the time that gives the most hits (dotted line at zero) would result in most balls being hit upwards. Subjects clearly tend towards hitting balls horizontally: most points are above the dotted line. They aimed to arrive later when hitting more slowly (paired *t*-test: $t_9 = 4.0$; $p = 0.003$).

3.2. Tapping in synchrony

The standard deviation in the timing of the individual digits was significantly smaller when the fingers were moving faster just before the hit in order to achieve louder taps (Fig. 5; paired *t*-test: $t_5 = 3.2$; $p = 0.024$). Again, we used the equation presented in Section 2.4 to separate the standard deviation in timing into a part that we attribute to errors in judging the distance that is to be moved and a part that we attribute to other factors that limit timing precision. The average value that we obtained for the standard deviation in judging the distance is 2.2 mm with a standard deviation across subjects of 1.1 mm. The average value for the remaining aspects of timing is 6.2 ms, with a standard deviation across subjects of 1.6 ms.

The mean amplitude of the movements was about 1.5 cm for soft taps and about 5 cm for loud ones. The average interval between the taps was about 500 ms, with a standard deviation (within sessions) of about 20 ms, irrespective of the kind of tap. The digits were in contact with the surface about 27% of the time for soft taps and about 30% of the time for loud ones. The main difference between the two kinds of taps, except for the difference in speed at impact, is therefore the difference in movement amplitude. When isolating the standard deviation in timing we assume that the precision in judging the distance that is to be moved ($\sigma_{distance}$) is independent of the movement amplitude, but this is far from certain. If it were proportional to the amplitude we would expect little benefit (in terms of precision) from moving faster because faster movements were mainly achieved by increasing movement amplitude. If precision in judging the distance decreases with movement amplitude, but less than proportionally, part of the variability that we attribute to imprecision in timing should actually be attributed to imprecision in judging the relevant distance, because we distinguish between the two on the basis of the influence of velocity. The standard deviation in judgments of timing may therefore be smaller than 6 ms. Correlated variability in judging the distance that the two fingers need to move (for instance as a result of misjudging the height of the tapping surfaces) will hardly influence the tapping asynchrony, so the standard deviation in judging the relevant distance may be larger than 2 mm.

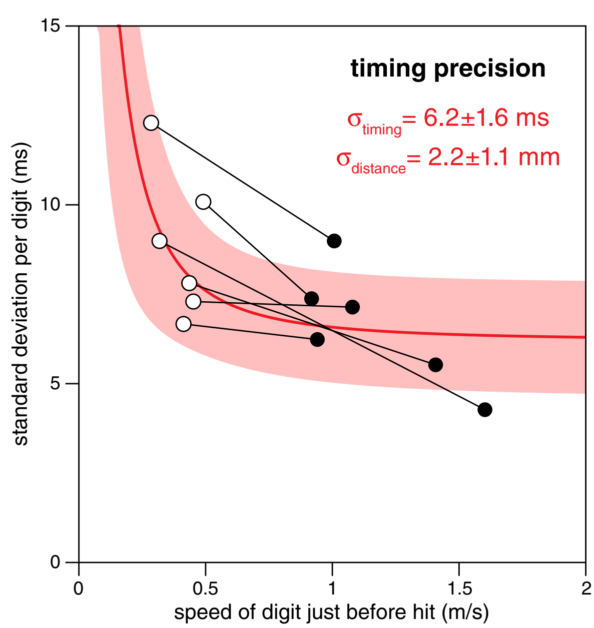

Fig. 5. Results of the synchronous tapping task: standard deviation in the timing of each digit as a function of the speed at which the digit is moving when it hits the surface. Open symbols: slow tapping. Solid symbols: fast tapping. Lines connect the individual subjects' values. The red curve and shaded area shows what one would expect (mean ± one standard deviation) for the mentioned values of σ_{timing} and $\sigma_{distance}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

Our results confirm that hitting faster can help to achieve more precise timing (Newell, Carlton, Carlton, & Halbert, 1980; Schmidt et al., 1979). We attribute the improved timing to the fact that part of the temporal misjudgment is due to misestimating the distance to the desired point of interception (Brenner & Smeets, 2009; Brouwer et al., 2000; Schmidt et al., 1979). We obviously cannot be certain that there is no other reason for the speed of the movement to have influenced the timing precision. For instance, signal-dependent noise (Harris & Wolpert, 1998) may make faster movements temporally as well as spatially less precise. However, that could not explain our findings because it would make faster movements less precise, rather than more precise. Another possibility is that one may have a better judgment of the duration of a movement when moving faster, because moving faster decreases the duration of the movement (Ivry & Hazeltine, 1995; Keele, Pokorny, Corcos, & Ivry, 1985). However, this reasoning only holds for judgments that are made before the movement starts, and we know that hitting movements are adjusted as they progress (Brenner & Smeets, 2011a). Moreover, Doumas et al. (2008) found that neither movement amplitude nor tapping rate influenced the synchrony between the digits (for equal amplitude movements). They found a synchrony between the fingers that was comparable to that of our subjects' soft taps. We found better synchrony when subjects increased the movement amplitude to achieve a higher speed at impact, and thereby to hit 'louder'. Together, these findings support the idea that timing precision specifically depends on the speed at impact.

Arriving at a certain position in synchrony with an external stimulus, such as a moving ball, is quite different from attempting to make movements of a particular duration. While moving towards a ball, one is constantly updating one's estimate of the desired place and time of interception on the basis of new, more reliable information (Brenner & Smeets, 2011a; López-Moliner, Brenner, Louw, & Smeets, 2010). When attempting to tap a certain rhythm, one does not receive new information about the desired moment of interest until after it has passed (or not at all if the task is to continue tapping a previously presented rhythm). Our subjects' precision in achieving 500 ms intervals is similar to that of the subjects in Doumas et al. (2008), despite the fact that our subjects continuously heard the tones whereas theirs had to reproduce a previously heard rate, so apparently sensory feedback after each tap is not very critical for the temporal precision of tapping. Since tapping in synchrony with tones requires one to predict the moment of the next tone in advance, the temporal precision depends on the length of the intervals (Doumas & Wing, 2007; Repp, 2005). Note, however, that we compare temporal precision in hitting a ball with the synchrony between the two hands, rather than with the synchrony between the taps and the tones.

We separated the overall temporal variability in each of our two tasks into a part caused by misestimating the distance that is to be moved and a part due to a limited temporal resolution. This was done by assuming that moving fast only reduces the temporal variability by reducing the consequence of misestimating the distance that is to be moved. This analysis provides estimates for how precisely one can judge the distance that is to be moved as well as estimates for timing precision. The former estimates are quite reasonable: they are much smaller for the finger tapping task than for hitting with a bat, and in the latter case the standard deviation is only about double the variability in the position of the ball across trials (variability determined in the direction of the bat's motion when hit). The standard deviation in timing that we estimate in this manner is about 6 ms.

For our hitting task, several factors could limit the precision of timing. The most obvious is that one has to judge when the ball will reach a certain position or where it will be at a certain time. Considering reported values for the precision of visually judging velocity and separation, and a minimal latency for adjusting movements to new visual information, we have reasoned that people should be unable to predict when a target will reach a given position with a better precision than 7 ms (Brenner & Smeets, 2011a). We here show that they must be able to do a bit better. Perhaps judgments about real balls are more precise than judgments about targets on a screen (for instance because several sources of information can be combined; Rushton & Wann, 1999). Moreover, the balls in our experiment were always released from the same height, so subjects could use additional timing information based on previous trials (de Lussanet, Smeets, & Brenner, 2001) or knowledge of gravitational acceleration (Zago, McIntyre, Senot, & Lacquaniti, 2009) to improve their precision. Whatever the reason, it seems reasonable to assume that visually predicting the ball's position at some later time, or predicting the time at which the ball will reach some position, is a major factor in limiting timing precision.

Another factor that could limit temporal precision in our hitting task is that people have to judge the bat's vertical and lateral position with respect to the ball. We estimated that the standard deviation in judgments of the bat's distance from the anticipated interception point at the critical moment is 4.4 cm. Similar variability in judging the bat's vertical position with respect to the anticipated interception point would correspond with a timing error of about 5 ms in judging the ball's position (because the ball is moving at about 8.7 m/s). However, the required vertical displacement may be judged more accurately because the vertical displacement is smaller, and the bat's path is probably adjusted more efficiently in response to new information during the movement than is the bat's speed (Brenner & Smeets, 2011a), so the variability is likely to be smaller. Variability in judging the bat's lateral position with respect to the anticipated interception point probably has a negligible influence, because the bat is oriented more or less horizontally, along what we consider to be the lateral direction, at the time of the hit, so that such variability will hardly influence the quality of the hit.

Finally, people must be able to reach the judged position with the bat at the time they intend to. Theoretically we would have hoped to estimate how well people can do so from the second, bimanual tapping task. However, the results of the tapping task raise a dilemma. In that task, there should be no sensory contribution to limit timing precision, so the variability should be smaller, but we find about the same standard deviation (just over 6 ms). Thus, we could be incorrect in asserting that visual judgments dominate hitting precision (as we do above), or else there must either be a fundamental difference between movement precision in the two tasks or an additional source of variability in the tapping task. The most parsimonious explanation is that visual errors are negligible, so both tasks reveal the temporal limits of movement production. However it seems quite unlikely that visual judgments are much more precise than 6 ms. In fact, it is already hard to believe that visual judgments can be so precise (Brenner & Smeets, 2010; Brenner & Smeets, 2011a; McLeod & Jenkins, 1991). On the other hand, we see no reason other than one based on speed to suspect that finger movements would be *less* precise than swinging a bat. We therefore favour the possibility that some aspect of judging the correct time to tap differs for the two hands, so that attributing all errors in synchrony to motor variability is not justified. We have no direct evidence for this, but there is some evidence that the precision of motor timing *can* be more precise than 6 ms, at least in throwing tasks (Hore & Watts, 2011; Smeets, Frens, & Brenner, 2002).

In any case, the combination of anticipating when a falling ball will be at a certain position (or where the ball will be at a certain time) and the ability to reach the anticipated position at the anticipated time must combine to give a timing precision of about 6 ms. Similarly, one must be able to time the moment that a finger reaches an anticipated contact point with a precision of about 6 ms. In the present study we demonstrate that additional temporal variability is introduced by misjudging the distance to the position in question, so that the anticipated position does not coincide with the true position. Thus, to obtain a high temporal precision it is advantageous to move fast.

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