

Timing an Attacking Forehand Drive in Table Tennis

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Comparison of initial and terminal temporal accuracy of 5 male top table tennis players performing attacking forehand drives led to the conclusion that because of a higher temporal accuracy at the moment of ball/bat contact than at initiation the players did not fully rely on a consistent movement production strategy. Functional trial-to-trial variation was evidenced by negative correlations between the perceptually specified time-to-contact at the moment of initiation and the mean acceleration during the drive; within-trial adaptation was also evident for two of the Ss. It is argued that task constraints provide the organizing principles for perception and action at the same time, thereby establishing a mutual dependency between the two. Allowing for changes in these parameters over time, a unified explanation is suggested that does not take recourse to large amounts of (tacit) knowledge on the part of the S.

Expert performers in ball games, such as baseball (Hubbard & Seng, 1954), table tennis (Bootsma & Van Wieringen, 1988; Tyldesley & Whiting, 1975), and field hockey (Franks, Weicker, & Robertson, 1985), have been shown to execute their drives with remarkably consistent movement times, that is, the time between the first persistent forward motion of the bat, stick, or racquet and the moment of ball contact varies little over trials. In fact, such consistency is, at least in table tennis, one of the characteristics that clearly distinguishes expert performers from novices (Bootsma, Den Brinker, & Whiting, 1986; Tyldesley & Whiting, 1975).

Operational Timing

By tradition, such consistency on the part of expert performers has been interpreted as evidence for a motor program theory of control (Franks et al., 1985; Schmidt, 1975, 1982; Tyldesley & Whiting, 1975). The program is thought to be a set of instructions for movement, organized ahead of its execution (Zelaznik, 1986). The consistency of movement is thus argued to be the result of consistent motor programming. As Tyldesley and Whiting put it:

It is suggested that the performer *first* selects a stroke from within his repertoire which best suits the occasion There is thus a predetermined plan of response for that situation. This plan will lead to a concise motor programme which will have associated with its correct execution a *real duration* Tr [Time Real]. Through an a priori determination of the response, the subject "knows" Tr and, within the error tolerance limits defined by the task difficulty, an *initiation point* for that programme will be dictated as forcefully as any other rule within the real world in which the performer is operating. (p. 173)

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The expert performer, that is, in the terms of Tyldesley and Whiting (1975), the consistent motor programmer, is thus faced with only the problem of when to initiate the drive, rendering continuous input monitoring during execution superfluous and thus reducing the reafferent load on the system. The central point of this operational timing hypothesis is the a priori knowledge on the part of the performer of the real-time duration of the movement that is presumably established during acquisition. Note that the credibility of the hypothesis rests on the assumption that the temporal initiation point can be selected accurately enough to remain within the error tolerance limits defined by the difficulty of the task.

Because the operational timing hypothesis does not require perceptual monitoring during execution, finding nondecreased performance under conditions in which visual information is not available during execution would corroborate this hypothesis. However, most studies on interceptive actions have found maximal performance to occur only under full visibility conditions (Sharp, 1975; Whiting, Gill, & Stephenson, 1970). Thus, although successful performance is in fact possible on the basis of only limited time spans of visual information, performance under such conditions never equals that of the normal situation of continuously available information. If the continuous availability of information has such a marked effect on performance, the step to stating that this information could be used continuously to aid performance follows naturally.

Continuous Guidance

Many experiments have been reported on the so-called minimal visual feedback processing time (Beggs & Howarth, 1972; Carlton, 1981; Carlton & Carlton, 1987; Gielen, Van den Heuvel, & Denier van der Gon, 1984; Quinn & Sherwood, 1983). Although opinions differ as to its exact duration, most of those experimenters agreed that significant amounts of time elapse between the visual indication that something has to be changed and its subsequent motor implementation. In all such studies, however, information has been conceived in its traditional interpretation of the amount of uncertainty (Shannon & Weaver, 1949) rather than in terms of a lawful

specification of events (Gibson, 1979) and invoked, moreover, an arbitrary coupling between stimulus and response. Having to increase or reverse the speed of movement on the basis of some light coming on at some unpredictable moment during movement execution, as in the Quinn and Sherwood (1983) study, can hardly be compared with, let alone generalized to, movement execution on the basis of a continuous information flow specifying present and future events (Bootsma, 1989; Fitch & Turvey, 1978; Kugler, Turvey, Carello, & Shaw, 1985; Lee, Young, Reddish, Lough, & Clayton, 1983; Runeson & Frykholm, 1983; Todd, 1981; Turvey & Carello, 1986; Warren, Young, & Lee, 1986). Experiments in which subjects operate under real-life conditions can be logically expected to render a more thorough insight into the way behavior is coordinated with events in the environment.

McLeod (1987) reported an experiment in which expert cricket batsmen were confronted with unexpected changes in the trajectory of a bowled ball, brought about by having the ball bounce on an irregular surface. Subjects were shown to be unable to adapt their swing to the new circumstances for at least the first 190 ms following such changes. These results appear to indicate that ongoing movement cannot be altered for a considerable (i.e., 190 ms) amount of time following initiation.

Two points, however, should be noted here. In the first place, mechanical factors such as the moment of inertia have to be considered. When swinging a cricket bat at full speed, the impulse (the product of the amount of force and the duration of its application) needed to deviate the bat from its initial trajectory is considerable. From the kinematics of the bat alone, it cannot be decided when the subject started to apply the force that eventually (after 190 ms) caused the bat to change direction. In the second place, a nontrivial distinction exists between using visual information in correcting an unexpected error and visual guidance of movement during the natural unfolding of the act. The latter was addressed by Lee et al. (1983) in an experiment in which subjects were asked to jump up to hit a falling ball dropped from varying heights. Monitoring the knee and elbow angles of the subjects during the act, Lee et al. demonstrated that the magnitude of these angles depended continuously on perceptual information specifying time-to-contact between the ball and the subject, with visuomotor delays ranging from 55 to 130 ms. Thus, in the case of Lee et al.—involving an act with a duration of some 700 ms—visual information was shown to be used not only to determine the temporal initiation point of the act, as Tyldesley and Whiting (1975) proposed, but to guide the movement during the subsequent execution period as well. One obvious difference between the task used by Lee et al. and that used by Tyldesley and Whiting (1975) is the duration of the movement execution phase. The present experiment therefore addresses the question whether the continuous guidance demonstrated by Lee et al. is to be found during execution of a rapid sporting action, the attacking forehand drive in table tennis, an action that, contrary to jumping up to hit a falling ball, is completed within less than 200 ms.

Constraints in Goal-Directed Hitting

Five Dutch male top table tennis players were, in the present experiment, required to hit an approaching table tennis ball

as hard and as accurately as possible onto a target on the opposite side of the net, utilizing an attacking forehand drive technique (i.e., a nonspin smash). On average, 30 of a block of 40 balls hit the target, with a mean ball velocity of 17 m per second. What constraints must be met in order to achieve this? First of all, the player must ensure that the table tennis bat (paddle) contacts the ball. Second, the bat has to travel with a high velocity at the moment of ball/bat contact to impart a large impulse onto the ball. Finally, the bat must be traveling in a precisely controlled direction at the moment of contact in order to propel the ball onto the target.

We first consider how the player ensures that the bat contacts the ball. What the player needs to see is when the ball will arrive in his "action space" (Von Hofsten's, 1987, term). Lee (1976, 1980) showed that such temporal information is specified directly in the inverse of the relative rate of dilation of the closed optical contour generated in the optic array by the approaching ball (denoted *tau* by Lee), which specifies the time-to-contact between the observer and the ball if velocity of approach remains constant. Differences between the actual time-to-contact and the value specified by *tau* are negligible at short times-to-contact (<300 ms for objects accelerating under gravity), even if the approach velocity is not constant (Lee et al., 1983).¹

By making use of *tau*, the player can pick up directly when the ball will reach him. Of course this does not yet ensure that the ball will be contacted, for this requires an action on the part of the player. This action must thus be geared to *tau*. Tyldesley and Whiting (1975) suggested that a synchronization between movement and visual information can be achieved by producing the same movement over and over again—that is to say, with very little variation between drives—so that the (expert) player is facing only the problem of when to initiate the drive. It is clear that in the case of a low-variability drive, the player could wait until *tau* reaches some critical value, which would then serve as an initiation signal for execution of the drive. Such an approach is similar to the way in which plummeting gannets have been described to ensure a safe entry into the water (Lee & Reddish, 1981).

The second criterion for successful performance—a high bat velocity at the moment of ball/bat contact—could be helpful in bringing about such consistency. Schmidt and Sherwood (1982) argued that the execution of a movement at high velocity leads necessarily to a more consistent movement pattern, a consequence that can be explained in terms of impulse-variability principles. Thus, the execution of a (near) maximal velocity drive would tend naturally to be more consistent than a lower velocity drive. This was in fact found by Bootsma and Van Wieringen (1988) in that execution of an attacking forehand drive in table tennis with a lower velocity was associated with an increase in movement time variability.

¹ The inverse of the relative rate of dilation of the closed optical contour generated by the ball in the optic array, *tau*, specifies the distance between ball and observer divided by the relative rate of approach, a quantity denoted the *tau margin*. Lee et al. (1983) showed that people gear their actions to the *tau margin*, which can be directly picked up through the optic variable *tau*, and not to the "real" time-to-contact in the case of a discrepancy between the two.

Because of this high velocity, however, the third criterion the player has to meet—controlling the direction of travel of the bat at the moment of ball/bat contact—imposes very strict temporal demands on the player. Not only must the player ensure that the bat contacts the ball but also he must do so at the moment the bat is traveling in a specific direction. As noted before, subjects in the present experiment managed to get 75% of the balls, on average, into the target area. Because the target had a diameter of 55 cm and was located some 2.5 m away from the point of contact (near the leading edge of the table), this implies that at least 75% of the balls have been contacted with the direction of travel of the bat not varying more than 6° around the line through the center of the target. Assuming a normal distribution, the standard deviation of the direction of travel of the bat at the moment of contact must have been therefore 5.2° . As seen later, angular bat velocities at contact of $800^\circ/\text{s}$ are quite common, which means that the players have to time their moment of contact with a precision of, at maximum, $5.2/0.800 = 6.5$ ms.

Together, the aforementioned constraints reflect the very narrow operating space of the expert. In order for him to perform within such a narrow operating space, two main possibilities have been suggested. On the one hand, the expert might produce a standard, unaltered, low-variability drive, thus remaining within the limits of the operating space as long as he can initiate his drive accurately enough. On the other hand, as conditions such as his position, posture, and preparedness change, he might produce a drive revealing functional variation, that is, the drive would be adapted to meet the requirements of the specific situation. Given the issues raised in the preceding paragraphs, this experiment was designed to identify the way in which expert table tennis players operate in order to meet the severe time constraints associated with executing attacking forehand drives that are to land the balls on a designated target.

Method

Task

The subjects were required to return table tennis balls as fast and as accurately as possible onto a circular target (55 cm in diameter) on the opposite side of the net, using an attacking forehand drive technique. A Sitco RII-s ball projection machine delivered balls with a frequency of 40 per minute to a former Dutch table tennis champion, who then played the balls to the subjects. This procedure allowed for both consistency in the way the balls were delivered to the players and a more natural setting.

Subjects

Five male right-handed subjects participated in the experiment. All played in the highest Dutch national league and were considered therein as "top" players. Their ages ranged from 18 to 24 years.

Procedure

All balls were delivered to the subjects with a speed of approximately 4 m/s. They all bounced on the table in a 25×25 cm marked square in the middle of the right-hand side of the table, some 30 cm from the leading edge. After playing four blocks of 40 trials, to allow

for adaptation to the experimental environment, during the next block of 40 trials seven drives were filmed (20th–26th). The camera (Teledyne), running at a speed of 125 frames per s, was placed perpendicular to the table at a distance of 5 m from the subject, 1.5 m above the ground. Above the player a mirror of 2.0×1.5 m was suspended under a 45° angle, so that in one camera shot both a side and a top view of the action were recorded.

Data Analysis

The films (Kodak 4X Reversal 400 ASA) were projected by means of a NAC (DF-16b) 16-mm projector onto an opaque screen. Mounted on the screen was a SAC 14-in. X-Y tablet, connected to an Apple II microcomputer. Frame-by-frame analysis of ball, bat, and eye in the sagittal plane and ball, bat, elbow, and shoulders in the transversal plane allowed the coordinates of these marked points to be read into the computer and stored on floppy disk. Later, the data were transferred to a much faster Cyber 175–750 main frame for further processing. The displacement data were filtered with a recursive, second-order Butterworth filter, with a cut-off frequency of 8 Hz. This procedure was run through twice in order to negate the phase shift (Wood, 1982). The 8-Hz low-pass cut-off frequency was chosen, because a fast fourier transform of the displacement data of the bat showed that 93% of the frequency signal was accounted for in this way.

The movement analysis included the position of the bat at the moment of initiation of the drive (defined as the moment the velocity of the bat in the sagittal plane changed from negative to positive) and at the moment of ball/bat contact (defined as the moment the ball velocity changed from positive to negative). Movement time was defined as the amount of time elapsed between the initiation of the drive and the moment of ball/bat contact. Velocity and acceleration of the bat were obtained by calculating the first and second time derivatives of the displacement data, by the first central difference method (Lees, 1980). The direction of travel of the bat was calculated as the derivative of Y position with respect to X position. The rate of change of the direction of motion was obtained by calculating the first derivative of these data with respect to time.

Perceptually related parameters were also analyzed. The tau-margin, which can be directly picked up through the use of tau, was calculated as the quotient of the distance between the eye of the player and the ball and its rate of change.

Results and Discussion

Initial and Terminal Accuracy

In Table 1 the means and standard deviations of selected kinematic variables over the seven drives are presented for each subject individually. A first point to notice is that the standard deviation for the spatial location of the bat at the moment of ball/bat contact is always larger than for the spatial location of the bat at initiation.² Similar results have been reported by Anderson and Pitcairn (1986) with respect to dart throwing: During execution of the throw an increasing spatial variability was found, a finding they associated with a type of

² The difference in magnitude of the spatial variability of the bat at initiation and at ball/bat contact could, in this experiment, partly be the result of a (per definition) lower spatial resolution when the bat is moving with a high velocity, as is the case at the moment of ball/bat contact, whereas at initiation the bat is not moving at all.

Table 1
Means and Standard Deviations Over Seven Drives
of Selected Kinematic Parameters of 5 Top
Table Tennis Players

	IP (in cm)	HIT (in cm)	LEN (in cm)	MT (in ms)	TAU _{ip} (in ms)
Subject 1					
<i>M</i>	118.8	49.8	69.0	158.4	228.2
<i>SD</i>	3.6	4.0	3.7	20.9	21.9
Subject 2					
<i>M</i>	105.6	43.1	62.6	105.4	146.0
<i>SD</i>	4.3	8.0	4.6	5.3	14.1
Subject 3					
<i>M</i>	116.2	41.3	74.9	162.2	180.1
<i>SD</i>	2.3	3.7	2.9	8.7	15.2
Subject 4					
<i>M</i>	93.0	33.2	59.7	92.0	123.5
<i>SD</i>	5.4	6.1	2.3	4.8	7.7
Subject 5					
<i>M</i>	116.4	45.4	71.0	177.8	219.7
<i>SD</i>	1.8	2.7	4.7	19.0	28.3

Note. IP = location of initiation point of the drive relative to the leading edge of the table; HIT = location of the point of ball/bat contact relative to the leading edge of the table; LEN = length of the drive; MT = movement time between initiation and ball/bat contact; TAU_{ip} = tau margin at the moment of initiation of the drive.

open-loop control. If the movement was to be under open-loop control, with the spatial initiation point controlled before onset of the throw, an increasing spatial variability is to be expected during the repeated execution of the throw due to "noise" from within and from outside the system. The difference between skill levels in dart throwing, they argued, is reflected in the band width of the variability at the end of the throw, that is, at the moment of dart release. Although variability at the moment of release of the dart results in decreasing performance in this closed skill, the same does not necessarily hold in the context of this experiment, because as we argue below, the direction of travel of the bat at the moment of ball/bat contact is the more important determining factor for success. Therefore, the interpretation offered by Anderson and Pitcairn (1986) for their results need not apply to ours. A second point to notice is that the standard deviation of the length of the drive is smaller than it should be if the spatial location of the bat at the moment of initiation and that at the moment of contact were uncorrelated.

As was done for spatial accuracy, initial and terminal temporal accuracy were also compared. Initial temporal variability is given by the variability of the value of the tau-margin at initiation, that is, by the variability over drives in the time it will take from initiation onward for the ball and the observer to collide if the present conditions pertain. The use of tau as an information source for guiding the initiation of the drive has been demonstrated elsewhere (Bootsma & Van Wieringen, 1988) and is therefore not addressed here.

Terminal accuracy, that is, the variability of timing accuracy at ball/bat contact, can be derived from the variability of direction of travel of the bat at the moment of ball/bat contact and the (mean) rate of change of this parameter. Because the player is attempting to land the balls on the

target, the variability of the direction of travel of the bat at the moment of ball/bat contact—which is directly responsible for the direction of travel of the ball immediately following contact—determines the outcome score. Because the direction of travel of the bat is changing rapidly in the neighborhood of contact, an indication of the timing accuracy at that point can be obtained from the quotient of the standard deviation of the direction of travel and its mean rate of change. In Table 2, data pertinent to this argument are presented.

Comparison of the terminal timing accuracy (last column of Table 2) with the standard deviations³ of the tau-margin at the initiation of the drive (last column of Table 1) indicates that for all 5 subjects the timing accuracy manifest at ball/bat contact was not apparent at initiation, the tau-margin at that point, and, for that matter, the movement time between initiation and ball/bat contact, being much too variable. With the credibility of the operational timing hypothesis of Tyldesley and Whiting (1975) resting on the subject's ability to select the temporal initiation point accurately enough to remain within the error tolerance limits of the task, it must be concluded that such a control strategy does not seem viable as an explanation of the way in which top table tennis players operate in order to meet the severe time constraints of executing an attacking forehand drive. As it turns out, the timing accuracy at initiation is factually less precise than at ball/bat contact. Therefore, the observed variance between trials must be interpreted as being functional, rather than noise. It is also noteworthy that a (somewhat) greater spatial variability was found for the location of the bat at ball/bat contact than at initiation (see Figure 1). Given that the terminal timing accuracy is better than the initial timing accuracy, intensive parameters should reflect this update. Figure 1 (panel A) illustrates that positional parameters do not qualify. It is not the *location* of the bat at the moment of ball/bat contact that is essential for getting the ball into the target area but rather the *direction* of travel of the bat at that moment.

Direction of Travel of the Bat During the Drive

If, indeed, the direction of travel of the bat at the moment of ball/bat contact is (one of) the variable(s) being controlled by the players, it is in this variable that the increasing temporal accuracy, as found in the previous section, should be reflected. Because the majority of changes of movement direction occurred in the transversal plane, we restricted our analysis to those data only. In Figure 1 (panel D) the direction of movement during the seven drives of an exemplary subject is depicted.

The most striking feature of Figure 1, panel D, is that the variation in direction of travel of the bat declines toward the moment of contact. This was observed for all 5 subjects. Thus it can be seen that, in fact, variability in essential features of the movement pattern does not increase toward the end of the action, as Anderson and Pitcairn (1986) argued, but, in contrast, decreases. The question to be addressed next is how such "homing in" is accomplished.

³ Note that the terminal accuracy measure that is used is, factually, a standard deviation.

Table 2
Means and Standard Deviations of the Direction of Travel of the Bat (Dir) and Its Rate of Change (Vdir) at the Moment of Ball Contact, and the Timing Accuracy (Tim. Acc.) at Contact Calculated as the Quotient of the Standard Deviation of Dir and the Mean Vdir

Subject	Dir		Vdir		Tim. Acc. (in ms)
	M (in rad)	SD (in rad)	M (in rad/s)	SD (in rad/s)	
1	-0.48	0.024	-11.8	1.3	2.03
2	-0.26	0.034	-16.3	1.4	2.09
3	-0.11	0.035	-13.7	1.1	2.55
4	-0.40	0.063	-15.3	0.9	4.11
5	-0.28	0.076	-16.1	1.0	4.72

Note. Dir is expressed as the angle between the direction of travel of the bat and the line perpendicular to the leading edge of the table.

Dependency of Perceptual and Motor Components

In a previous article (Bootsma & Van Wieringen, 1988), we argued that a correlation between the tau margin at initiation and the maximal bat velocity attained during the drive could be helpful in understanding the type of control underlying the movement execution. As the bat is gathering velocity right up to the moment of ball/bat contact (i.e., the acceleration at impact is greater than zero), it was argued that if consecutive drives were to be regarded as repeated execution of the same movement pattern, the occasions on which the drive was initiated somewhat earlier in time (implying a larger tau-margin at initiation) should be associated with larger velocities at ball/bat contact. The result of this would be a positive correlation between the tau-margin at initiation (τ_{ip}) and bat velocity at contact. A negative correlation, on the other hand, was argued to be indicative of trial-to-trial adaptation of the drives, early initiation being associated with a slower swing and late initiation with a faster one.

In the present study we decided, for several reasons, not to use maximal, that is, contact, velocity but mean velocity as well as mean acceleration during the drive. First, as the player may try to attain the same velocity at impact every time, thus controlling the distance traveled by the ball after impact, mean velocity gives a better impression of trial-to-trial variation. Indeed, mean velocity was found to show a greater variance than maximal velocity (coefficient of variation of maximal and mean velocity being, respectively, 3.9% and 10.6% on average). Second, mean acceleration was included as a more direct reflection of force production. As the acceleration changed rapidly in the neighborhood of ball/bat contact (see Figure 1, panel C), small errors in the determination of the exact moment of contact could influence the precise establishment of the mean acceleration. Therefore it was decided that mean acceleration should be calculated from the moment of initiation up to the moment of peak acceleration and thus free this measure of any influences due to error in the assessment of the exact moment of ball/bat contact. Pearson product-moment correlation coefficients between τ_{ip} and mean velocity and acceleration of all 5 players are presented in Table 3 (first and second columns).

As is apparent, all players but one revealed negative correlations between τ_{ip} and mean velocity. Correlations with mean acceleration were all negative and relatively high. The lower correlation between τ_{ip} and mean acceleration of Subject 4 might suggest that this subject does not reveal the same amount of covariance that the others do. However, it can also be explained by a restriction-of-range argument: The very small ranges of the variables entering into the correlation mitigate against finding significant correlation coefficients (see Table 1). Nevertheless, a compensatory coupling between perceptual (tau) and motor (acceleration) components was evident for all subjects.

Adaptation of the Drive

To shed some light on the question of whether the observed changes occurred during the drive or were already present at initiation, the following procedure was adopted. For the first half and the last half of the duration of each drive, the mean acceleration was separately computed. Subsequently, correlations were computed between the mean acceleration of the first-half interval and τ_{ip} for each individual subject and between the mean acceleration of the second-half interval and τ_{ip} , with the mean acceleration of the first half partialled out.

If a relation was to be found for the last-half interval only, this would suggest that changes in acceleration were being induced during the drive, after having started out in a standardized manner. On the other hand, if a relation was to be found for the first-half interval only, this would imply that changes between trials were evident right from the start of the movement, with no extra corrections near the end. And last, finding relations in both the first- and last-half intervals, with the influence of the first half on the second half partialled out, would suggest that changes in acceleration were occurring during the total duration of the drive. Table 3 (third and fourth columns) shows the results of this endeavor.

As can be seen from Table 3, all correlations of the tau-margin at initiation and the mean acceleration during the first-half interval of movement were negative. Thus, already at the start of the movement, modifications between trials were evident. However, the same held, though less strongly—but all correlations were negative—for the second half of the movement, even though the first part had been partialled out. These correlations suggest that at least 2 subjects of this study, Subjects 3 and 5, amended their drives during execution. We now discuss whether these results can be corroborated from another angle, namely, the way the tau-margin changes over time as a result of both the motion of the ball and the player.

Wagner (1982) found that the final deceleration of house flies prior to landing was initiated at a specific tau-margin value, and a similar result was reported by Lee and Reddish (1981) for the wing-closing action of diving gannets. In human's, Lee et al. (1983) reported visuomotor delays in jumping up to hit a falling ball of 55–135 ms. If our top players were to have similarly short visuomotor delays, perceptually induced changes in acceleration should, in principle, be possible during their drives. Wagner reported that the tau margin

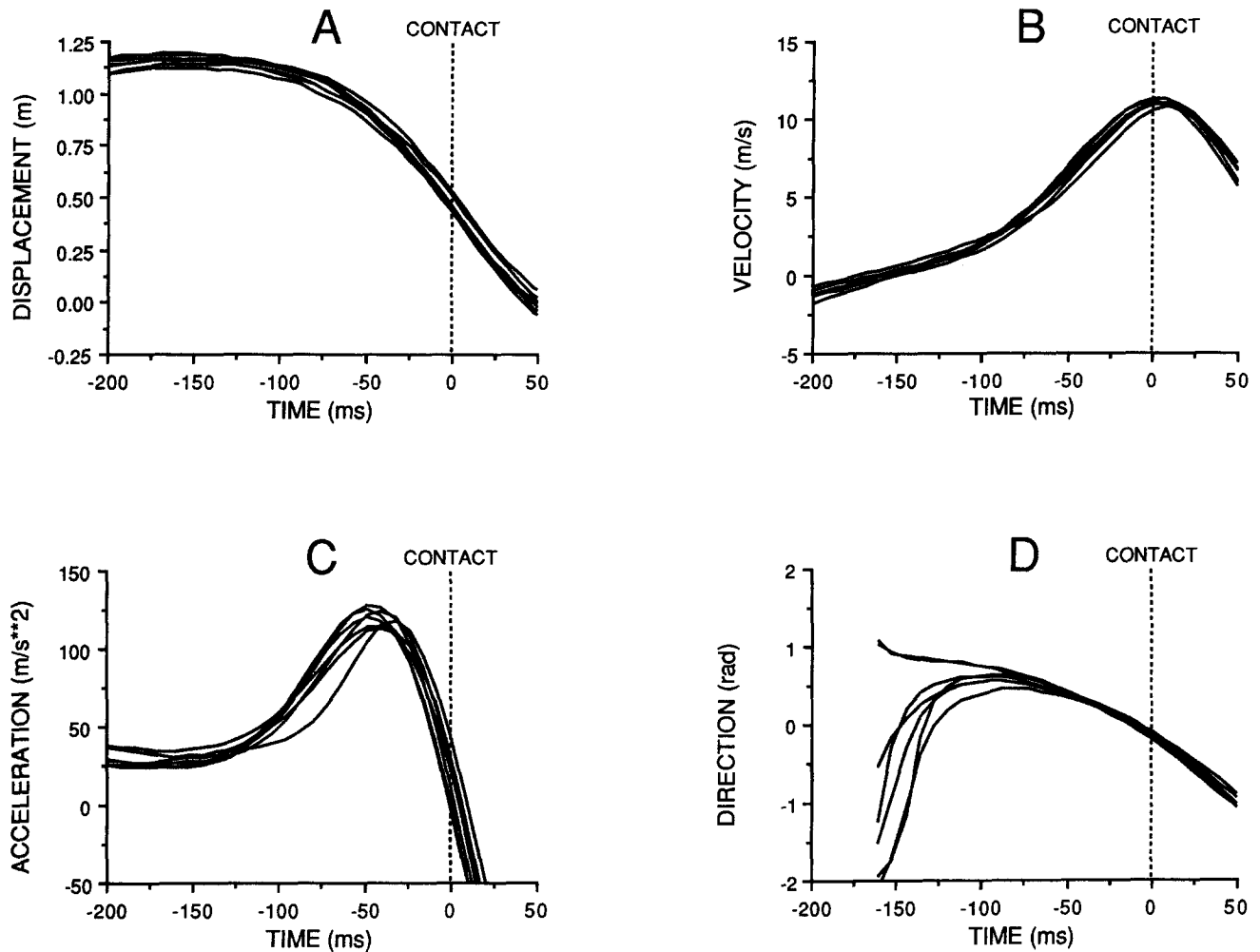


Figure 1. Displacement (A), velocity (B), acceleration (C), and direction of travel of the bat (D) profiles as a function of time for seven drives of top table tennis player.

(or more precisely the relative rate of dilation [RRD])⁴ which is the equivalent of the inverse of the tau-margin) reached its lowest coefficient of variation at the moment of onset of the final deceleration. That is to say, the house flies he observed

Table 3

Pearson Product-Moment Correlation Coefficients Between the Tau Margin at the Moment of Initiation of the Drive and Mean Velocity (Mean vel.), Mean Acceleration (Mean acc.), Mean Acceleration During First Half of the Movement, and Mean Acceleration During Second Half of the Movement, With the First Half Partialled Out

Subject	Mean vel.	Mean acc.	First half	Second half	Tcv _{min}
1	-.93	-.92	-.92	-.30	156
2	.23	-.66	-.45	-.29	105
3	-.24	-.54	-.51	-.59	106
4	-.54	-.49	-.34	-.19	122
5	-.58	-.93	-.76	-.68	116

Note. Tcv_{min} = time before contact at which the coefficient of variation of the relative rate of dilation reaches a minimum.

moved in such a way as to initiate their final deceleration before landing at a very specific RRD value. We would like to argue here that such a point of minimal coefficient of variation of the RRD is evidence of the ultimate moment of control being possible. In other words, the time between the point at which the coefficient of variation of RRD is smallest and the time of ball/bat contact would reflect the visuomotor delay of a player. The times before ball/bat contact at which RRD reached a minimal coefficient of variation over the seven drives were arrived at by calculating the value of RRD backward from the moment of ball/bat contact for every frame (steps of 8 ms) of every drive and consequently calculating the mean and standard deviation over the seven drives for every step. In Figure 2, the time course of RRD over seven drives is depicted for our exemplary subject, together with the

⁴ Whereas Wagner wrote of the relative retinal expansion velocity, we prefer to generalize this to relative rate of dilation (RRD), because it is a description of an information parameter that is available in the optic flow field and could also be registered by seeing species that do not have retinæ (cf. Gibson, 1979).

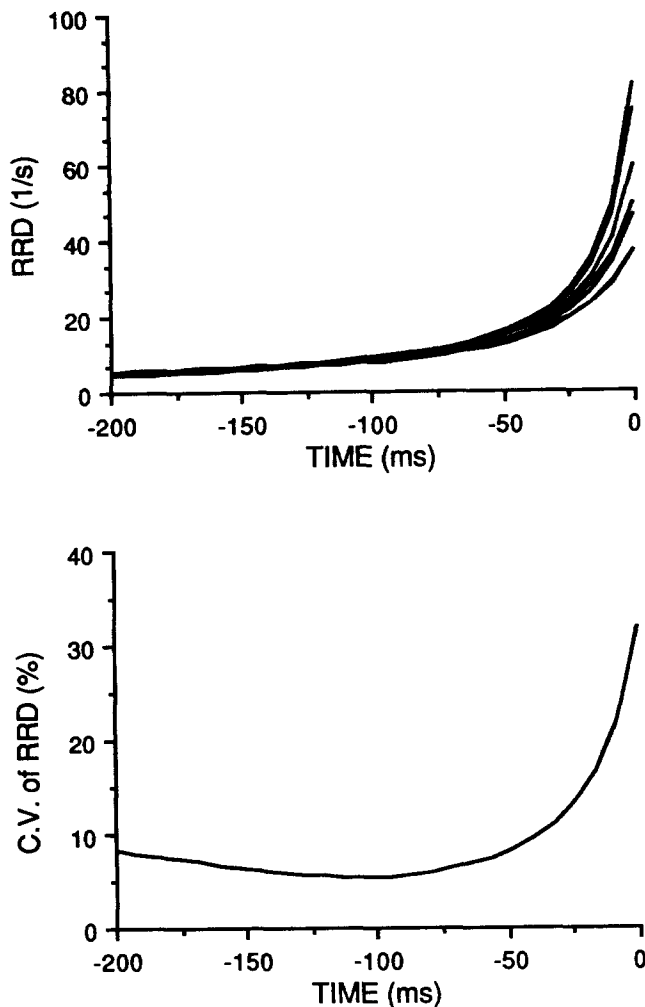


Figure 2. The relative rate of dilation (RRD) and its coefficient of variation as a function of time for seven drives of a top table tennis player.

time course of the coefficient of variation. The times before ball/bat contact at which the coefficient of variation of RRD was minimal are given in Table 3 (last column) for all subjects.

From a comparison of Table 3 (last column) and Table 1 (column 4), it is evident that for Subjects 1, 2, and 4 the time of minimal coefficient of variation of RRD occurred before or in the direct vicinity of the moment that the bat had started to move forward. (Note that the onset of the body preparation for the drive occurred much earlier than the onset of the forward movement of the bat.) Thus, for these subjects almost all between-trial variation in acceleration profiles must have been preset prior to the onset of forward movement of the bat. This is in perfect harmony with the result obtained with the partial correlation technique in that these 3 subjects revealed the lower correlations between τ_{ip} and acceleration during the second half of the drive. Subjects 3 and 5, on the other hand, revealed the higher correlations and were in the present analysis also found to reach their moment of minimal coefficient of variation of the tau-margin *during* movement

execution. Thus the results of these two types of analysis both lead to the conclusion that at least 2 of the 5 subjects were still altering their movement during execution.⁵

General Discussion

In the present study we investigated the way in which 5 top table tennis players performed attacking forehand drives that were to land the balls as fast and as accurately as possible on a target on the opposite side of the net. On the basis of existing literature on expert performance, it was expected that movement execution would be very consistent or, to be more specific, that movement times would not vary much from trial to trial (Franks et al. 1985; Hubbard & Seng, 1954; Tyldesley & Whiting, 1975). A control strategy on movement time, such as suggested in the operational timing hypothesis of Tyldesley and Whiting, has been interpreted to have the advantage of reducing the number of decisions to be made before performing the drive to only one, namely, when to initiate it. Put differently, producing a consistent movement time reduces the number of degrees of freedom that have to be controlled in task space (Fitch & Turvey, 1978; Saltzman & Kelso, 1987).

On the other hand, it should be realized that consistency is, of course, a matter of degree. Before dismissing the (small) trial-to-trial variations in movement execution parameters as "noise," one has to make sure that such variations do not serve functional purposes. The present analysis did in fact reveal that the observed variance was functional. On the basis of the standard deviation of the direction of travel of the bat at contact and its rate of change, the demands placed on terminal timing accuracy were computed. It was demonstrated that this accuracy was as precise as 2–5 ms and that both movement time and the perceptual variable assumed to be used by the subjects to determine when to initiate their drives, τ , revealed much higher standard deviations for all subjects. Thus, it must be concluded that, for the expert subjects of this experiment at least, a total reliance on consistent movement production is not feasible.

Given the fact that the subjects revealed a higher standard of timing accuracy at the moment of ball/bat contact than was to be found at initiation, this implies that the observed variance of movement execution has to be of a functional nature. A negative correlation was found between the magnitude of the tau-margin at initiation and the mean acceleration during the drive, that is, the closer in time the ball was to the player when the movement was initiated, the more force was applied during the stroke. This finding is interpreted to reflect the compensatory nature of the perception–action coupling of the player.

⁵ This finding of fine tuning during movement execution can also be understood from a physiological point of view: Whereas initiating the movement appears to consist of massive activation processes in many segments of the body in general and the central nervous system in particular already before the veridical onset of movement (Turvey, 1977), fine tuning of the arm movement through, for instance, tectospinal tracts could provide for the subsequent updating.

It could, of course, be argued that the subject had selected a specific movement (with a specific acceleration profile and accompanying movement time) and hence adapted the choice of the critical tau value for initiation to accommodate this selected movement time. However, this would demand a high spatial accuracy at contact—that is, making contact with the ball at exactly the preplanned position (in the preplanned configuration for that point of contact)—as the actual movement time would otherwise not match the selected movement time and would result in a different configuration of the body and hence a different direction of travel of the bat at that moment. Apart from the fact that such a control strategy places nontrivial demands on the player's predictive capabilities, we have seen that it is the direction of travel of the bat, rather than the spatial location of ball/bat contact, that imposes the severest constraints on the subjects.

Therefore, an alternative explanation is needed. The finding of fluctuations in one execution variable that are compensated for by fluctuations in another execution variable—a finding we propose to term *compensatory variability*—has been reported in a variety of different domains of human movement, such as pistol shooting (Aratyunyan, Gurfinkel, & Mirsky, 1969), handwriting (Teulings, 1988; Wing, 1978), grasping (Marteniuk, Mackenzie, & Leavitt, in press), juggling (Beek, 1989), continuous tracking (Darling & Cooke, 1987), and the production of targeted force impulses (Gordon & Ghez, 1987), although in most cases its relevance for motor behavior has not been fully recognized. In the present experiment, such compensatory variability was shown to exist between perceptual and motor components as well. Intercepting an approaching ball thus involves more than linking together the following two processes: (a) selecting a movement that requires a specific duration (assuming that this selected movement can be implemented accurately, this constitutes the motor component) and (b) initiating the movement at the adequate critical tau value (the perceptual component). On the basis of the present results, it is of course not possible to decide whether the action is, in a strict sense, continuously guided by perception. However, the obtained magnitudes of the visuomotor delays of 4 of the 5 subjects (ranging from 105 to 122 ms) do support the view that the optic flow field can at least be sampled with a higher frequency than might be inferred from visual reaction time studies in which static displays were used. Although perception and action can be analytically separated, such a separation does not have an ontological foundation (Bootsma, 1989; Fitch & Turvey, 1978; Turvey, in press). Rather, it appears to be the case that the task constraints, defined in task space (Saltzman & Kelso, 1987), provide the organizing principles for perception and action at the same time. Whether the act is performed a bit faster, initiated somewhat later, or performed more slowly, initiated somewhat earlier, appears to be inconsequential as long as a coupling between perceptual and movement variables is sustained.

Expressed formally, the selection of goal G defines a mutual relation between perceptual variables P and movement variables M , so that $P * M = f(G)$, where $*$ stands for "relates to." Inverting this relation we can get either $G = M(P)$ or $G = P(M)$. Thus, stating that the values of movement variables

are adapted to suit selected values of the pertinent perceptual variables is equivalent to stating that the values of perceptual variables are adapted to suit selected values of the pertinent movement variables. Neither has primacy, because it is in the selection of the goal that the relation between the two is established.

Moreover, such a relation can be made dynamic by allowing M and P to change over time: $P(t) * M(t) = f(G)$. During the unfolding of the act, as the information is becoming more and more precise (Fitch & Turvey, 1977; Lee et al., 1983), updates in P will be accompanied by updates in M and will lead to the appropriate changes in execution variables. Thus, trial-to-trial variations as well as within-trial adaptations, which were both found in this experiment, can be understood in this way, without recourse to extensive amounts of (tacit) knowledge having to be postulated.

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