OBSERVATIONS

Top-Level Players' Visual Control of Interceptive Actions: Bootsma and Van Wieringen (1990) 20 Years Later

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Using a two-step approach, Van Soest et al. (2010) recently questioned the pertinence of the conclusions drawn by Bootsma and Van Wieringen (1990) with respect to the visual regulation of an exemplary rapid interceptive action: the attacking forehand drive in table tennis. In the first step, they experimentally compared the movement behaviors of their participants under conditions with and without vision available during the execution of the drive. In the second step, through simulation they evaluated the extent to which a preprogrammed pattern of muscle stimulation acting on the dynamical characteristics of the musculoskeletal system could explain the patterns of movement observed, including the phenomena of kinematic convergence and compensatory variability. In this contribution, we show how methodological and conceptual shortcomings, pertaining to both parts of Van Soest et al.'s study, severely limit the impact of their findings. We argue that their conclusion—denying the possibility of visual regulation of rapid interceptive actions—cannot be upheld in the light of the existing evidence, while Bootsma and Van Wieringen's conclusion—in favor of the visual regulation of rapid interceptive actions in top-level players— still holds strong, even after 20 years. Irrespective of the trends of the moment, we suggest that both appropriate experimentation and principled theorization need to be deployed before a model-based predictive architecture can be considered as a serious alternative to a (more parsimonious) information-based control architecture.

Keywords: interceptive actions, information-based control, expertise, visuomotor delay, movement time

Hitting an approaching ball so as to propel it into the desired direction at the highest possible speed requires a high effector speed at the moment of contact. Such hitting actions are therefore characterized by a vigorous acceleration, resulting in a short movement duration. Field studies of hitting actions in sport activities such as baseball (Hubbard & Seng, 1954), squash (Wollstein & Abernethy, 1988), and table tennis (Bootsma & Van Wieringen, 1990) have indeed demonstrated that the time span separating the onset of the final acceleration of the end-effector from the moment of contact with the ball is often less than 200 ms. Traditionally, it has been assumed that such rapid movements must be executed in an open-loop manner because the movement duration would be too short to allow visual information to exert an influence during the movement.

Nevertheless, in a detailed analysis of the movements of top-level table tennis players performing a series of attacking forehand drives, Bootsma and Van Wieringen (1990) revealed the existence of several phenomena running counter to the accepted view of running off a pre-established motor program. First, as the movement unfolded spatiotemporal variability in task-relevant variables was found to decrease, culminating in a timing accuracy of less than 5 ms at the all-important moment of ball-bat contact. Second, as revealed by intraindividual correlations between the time remaining at initiation and mean acceleration during the movement, compensatory variability between informational and behavioral variables was observed, with movements starting a little earlier showing lower mean accelerations and movements starting a little later showing higher mean accelerations. Finally, two of the five players studied—with average movement durations of 162 and 178 ms and estimated visuomotor delays of 106 and 116 ms, respectively—demonstrated within-trial adaptations in their movement patterns, as evidenced by negative correlations between the time remaining at initiation and mean acceleration during the second half of the movement, when the acceleration during the first half was partialed out.

Embracing the traditional view that movements of such short durations cannot be modulated online, Van Soest, Bobbert, and Van Ingen Schenau (1994) suggested that the force-length-velocity relationships endowing muscles with visco-elastic properties might explain the phenomena observed by Bootsma and Van Wieringen (1990). Indeed, in a simulation study of the explosive movement involved in jumping to maximal height from a squatted initial position, they observed not only that a single muscle stimulation (STIM)

pattern could result in successful performance for a wide range of starting positions, but also that the "*application of this single STIM pattern resulted in decreasing variability in joint angles as the instant of takeoff is approached*" (p. 1397). Pertinent to the present purpose, they concluded their discussion of the squat jump simulations with the following suggestion: "*Generalizing this result to the task studied by Bootsma and Van Wieringen: a single STIM pattern is likely to exist that results in the extremely small variability of the important movement parameters at the instant of ball contact, irrespective of starting position. If such a single muscle stimulation pattern is used in reality, the control problem is reduced to starting the movement at the right instant of time. Although this constitutes a problem of its own, it should be manageable because of the direct visual perception of time to contact*" (p. 1401).

Following up on this suggestion, Van Soest, Casius, De Kok, Meeder, and Beek (2010) recently set out to replicate and extend Bootsma and Van Wieringen's (1990) study. By analyzing movement patterns of table tennis players performing forehand smashes under conditions with full vision and with vision obscured shortly after movement initiation, they experimentally sought to demonstrate that visual information becoming available during the execution of the drive was not used to guide the hitting action. This experimental study was complemented with simulation study—similar to that reported by Van Soest et al. (1994)—destined to demonstrate that a single pattern of muscle stimulation, triggered at an appropriate (presumably time-to-contact based) moment, could provide the mechanisms underlying the phenomena observed by Bootsma and Van Wieringen (1990). While the experimental study seemed to confirm the former hypothesis, the simulation study rendered mitigated results, leading Van Soest et al. (2010) to invoke the need for a supplementary control structure capable of model-based predictive control.

Although we strongly believe that replication (or nonreplication) of impactful findings is an important part of the scientific endeavor, we suggest that Van Soest et al.'s (2010) experimental and simulation studies suffer from a number of shortcomings, thereby severely limiting their implications. We argue that the methodology employed constrains the conclusions that may be drawn to a considerable extent, while the results are profoundly affected by the skill level of their participants—clearly lower than that of the participants in Bootsma and Van Wieringen's study. In the absence of any participant with a visuomotor delay short enough to allow online regulation, the comparison between conditions with full vision and vision obscured some time after movement initiation becomes of little theoretical interest. By triggering the STIM pattern at a nontheoretically founded different moment for each individual movement, the simulation study confounds the effects of timing with the effects of the modeled musculoskeletal dynamics that thereby unfortunately remain obscure. Finally, the proposition that, in the end, a internal model (i.e., a structure capable of model-based predictive control) would be required to explain the particulars of the movement patterns produced renders Van Soest et al.'s (2010) theoretical position incompatible with Van Soest et al.'s (1994) own argument that "*explanations of the control of explosive movements based on the assumption that such a complex internal representation is present in the CNS are not attractive*" (p. 1400).

We will address each of these issues in detail in the following sections, before arriving at the conclusion that the findings of Bootsma and Van Wieringen (1990) might be perceived as deranging, but seem to hold strong, even after 20 years.

Suppression of Vision

The particulars of the experimental manipulation of vision used by Van Soest et al. (2010) give rise to at least two methodological problems that raise questions with respect to conclusions allowed. The first is related to the timing of the obstruction of vision and the second to the methodological choice of suppressing rather than manipulating visual information.

Timing the Suppression of Vision

Bootsma and Van Wieringen (1990) advocate a continuous coupling between information and movement, with movement resulting from the integration of information into a dynamic law of control (Warren, 2006; for examples see Bastin, Calvin, & Montagne, 2006; Bootsma, Fayt, Zaal, & Laurent, 1997; Chardenon, Montagne, Laurent, & Bootsma, 2004; Fajen & Warren, 2004; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Put simply, in this perspective movement regulations lag updates in information by a visuomotor delay. Van Soest et al. (1994, 2010) advocate a type of control in which movement results from the triggering of a predetermined pattern of muscle stimulation acting on the dynamics of the musculoskeletal system. With the preparation and launching of the required motor commands by the central nervous system (CNS) necessarily occurring before movement onset, in this perspective the latest moment of potential influence of information is located at least one visuomotor delay before movement onset.

In Van Soest et al.'s (2010) study, vision was obscured shortly after onset of forward bat movement.[1] According to a continuous coupling perspective, information available until visual obstruction can be used in the regulation of action as long as there is sufficient time for the informational influence to play out (i.e., until one visuomotor delay before bat-ball contact). Thus, depending on the duration of the visuomotor delay of each player, information available at (or even shortly before) movement initiation—such as the current temporal distance between ball and player—might be used to regulate characteristics of movement—such as the acceleration. The presence of negative correlations between time-to-contact at movement onset and mean acceleration during the drive as found by Van Soest et al. (2010) under all experimental conditions is thus not surprising within the theoretical framework of Bootsma and Van Wieringen (1990). To truly test the hypothesis that movement results from the triggering of a predetermined pattern of muscle stimulation, the condition with unobstructed vision should be compared with a condition in which vision is obstructed one visuomotor delay before movement onset.

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[1] We estimate this delay to be at least 30 ms, for the following reasons. Van Soest et al. (2010) used an algorithm to detect the moment at which the forward acceleration of the bat exceeded 10 m/s^2, that is when the movement was already underway (delay conservatively estimated at 10 ms). On-line identification of this threshold implies transmission delays and double differentiation of the position data sampled at 200 Hz, minimally amounting to 15 ms. Finally, full closure of the spectacles occurred 5 ms after activation.

Suppression of Visual Information

Comparing conditions with and without vision, Van Soest et al.'s (2010) experimental approach is based on the hypothesis that an absence of differences between these conditions would be indicative of similar control processes. However, attractive as such a simple hypothesis might appear to be, it does not hold up against scrutiny. One cannot conclude that performance on a particular task is not based on visual information, simply because the task can also be successfully performed in the absence of vision. For instance, although we can successfully maintain posture in the absence of vision, the conclusion that, when available, vision would not be implicated in the control of posture is clearly contradicted by a large body of work (cf. Lee & Lishman, 1975; Stoffregen & Riccio, 1988). Directly pertinent to the present issues, Bardy and Laurent (1998) not only found that expert gymnasts could successfully perform a backward somersault with their eyes closed, but also that the within-participant variability over repeated trials in body orientation at landing was very small and comparable to that observed under conditions with the eyes open. A careful in-depth examination of the data however revealed that the conditions differed with respect to the evolution over time of body orientation variability, militating against the conclusion that in both conditions the somersault was controlled through a predetermined motor program.

Over the last decade, studies devoted to the identification of the perceptual information sources involved in the control of goal-directed behavior have moved from suppression methodologies in which visual information is globally or locally removed to decorrelation methodologies more subtly involving experimentally induced changes in selected elements during the execution of the task (e.g., Bastin et al., 2006; Fajen & Warren, 2004; Warren et al., 2001; see Savelsbergh, Whiting, & Bootsma, 1991 for an earlier example). Importantly, the two methodologies do not necessarily give rise to the same conclusions. In seeking to identify the perceptual information used in a locomotor pointing task, De Rugy, Montagne, Buekers, and Laurent (2000) found that removal of target expansion information (using a local suppression methodology) did not affect the accuracy of foot placement, nor any other aspect of the locomotor behavior produced, tentatively suggesting that expansion information was not used to perform the task under normal circumstances. However, when target expansion information was experimentally biased—with a decorrelation methodology based on the manipulation of target size during the trial—participants' locomotor behavior was found to be affected in a systematic way (De Rugy, Montagne, Buekers, & Laurent, 2001), thereby revealing that it did in fact play a role in the regulation of behavior.

Together, the above arguments indicate that the absence of differences between vision and no-vision conditions, such as reported by Van Soest et al. (2010), cannot be taken to imply that the same control mechanism was operating in both cases.

Differences in Level of Expertness

In the discussion of the observed differences in results between Bootsma and Van Wieringen's (1990) study and their replication, Van Soest et al. (2010) state that they "*have no means to substantiate the speculation that the difference in results is related to a difference in level of expertness of the participants in the two studies*" (p. 1052). Yet, there are several lines of converging evidence indicating that the participants in their study are not comparable to the participants in Bootsma and Van Wieringen's study. Let us first consider qualitative characteristics: Participants in the Bootsma and Van Wieringen study were five male players, between 18 and 24 years old and considered as "top players" within the highest Dutch national men's league. Participants in the Van Soest et al. study were seven female players, between 17 and 59 years old and qualified as "playing" in the highest Dutch national women's league. Hence, there are clear differences in gender, age, and classification level.

Second, let us consider the kinematic characteristics of the groups, as reported in the two studies. As noted by Van Soest et al., their players were positioned closer to the table, as evidenced by the (significantly different) locations of the bat at forward movement initiation and at ball-bat contact. Inspection of their Table 1 further reveals that, notwithstanding the instruction to hit the ball

Table 1

Between-Participant Averages and SDs (Between Parentheses) of Intraindividual Variability (SDs) (an Operational Measure of Consistency) of the Kinematic Variables Reported by Van Soest et al. (2010; SCKM&B) and Bootsma and Van Wieringen (1990; B&W)

	SCKM&B (*n* = 7)				B&W (*n* = 5)
	NSB	SO	SC	NSA	
IP (cm)	7.24 (5.68)	7.14 (3.28)°*	7.61 (3.59)°*	8.47 (6.56)	3.48 (1.47)
HIT (cm)	9.94 (7.00)	10.76 (6.03)*	8.95 (4.68)	10.97 (6.51)	4.90 (2.13)
LEN	6.63 (1.96)°*	7.42 (3.18)°*	7.26 (4.01)	6.26 (1.29)°*	3.64 (1.05)
MT (ms)	27.2 (6.9)°*	25.2 (12.1)*	23.7 (7.4)°*	27.8 (8.0)°*	11.7 (7.7)°*
TAUip (ms)	35.4 (9.8)°*	39.2 (14.5)°*	38.3 (15.7)°*	39.1 (6.3)°*	17.4 (7.9)
DIR (rad)	0.059 (0.024)	0.056 (0.009)	0.059 (0.019)	0.080 (0.027)°*	0.046 (0.022)
VDIR (rad/s)	1.66 (0.45)°*	1.64 (0.50)*	1.82 (0.65)°*	1.89 (0.68)°*	1.14 (0.21)

Note. Conditions of SCKM&B (first four columns): NSB = no spectacles before; SO = spectacles open; SC = spectacles closed; NSA = no spectacles after. Kinematic variables (rows): IP = location of the initiation point of the drive; HIT = location of the point of ball-bat contact; LEN = length of the drive; MT = movement time between initiation and ball-bat contact; TAUip = time to contact between ball and player at the moment of initiation of the drive; DIR = direction of travel of the bat at the moment of ball-bat contact; VDIR = rate of change of DIR.
° Significant ($p < .05$) differences with the data from B&W as revealed by a *T*-test for assumed equal variances.
* Significant ($p < .05$) differences with the data from B&W as revealed by Satterthwaite's approximate *T*-test for assumed unequal variances.

as hard as possible, the peak bat velocity attained by their participants was surprisingly low, ranging from 3.9 to 10.4 m/s for an average of 7.4 m/s. Clearly, several participants did not reach a sufficiently high peak bat velocity to allow qualifying their actions as smashes. As a concrete example, we suggest that with a movement extent of only some 30 cm and a peak bat velocity of less than 4 m/s Van Soest et al.'s participant 7 cannot decently be considered as a top table tennis player performing a smash.

Finally, let us consider the intraindividual consistency over repeated trials. It is generally agreed that expert performance is characterized by a high degree of consistency over repetitions under constant conditions (Schmidt & Lee, 2005). Table 1 presents the average intraindividual *SD*s over repeated trials for kinematic characteristics, for the seven participants from Van Soest et al. under each of their four experimental conditions and for the five participants from Bootsma and Van Wieringen. As can be seen from Table 1, Bootsma and Van Wieringen's players demonstrated superior consistency (smaller intraindividual variability) on all variables, with the difference reaching significance in 19 out of 28 comparisons, notwithstanding the small group sizes.

Taken together, we may therefore safely conclude—without any need for speculation—that the players studied by Bootsma and Van Wieringen were of a higher level of expertness than those studied by Van Soest et al. (2010). Differences in skill level, separating top-level athletes from others, have been suggested to be correlated with the control mechanisms operating (Bardy & Laurent, 1998; Wilson, Simpson, Van Emmerik, & Hamill, 2008). An indication that this would indeed be the case is to be found in an important difference between the studies of Bootsma and Van Wieringen and Van Soest et al., related to the estimated durations of the individual participants' visuomotor delays. We therefore address this issue in some detail in the next section.

Visuomotor Delays

Van Soest et al. (2010) suggest that fast interceptive actions with movement times less than 200 ms must be under open-loop control, simply because these "*movement times . . . are of the same order of magnitude as the visuomotor delay, which ranges between 100 and 200 ms*" (p. 1052).

If one accepts that dynamic visual information about the evolving player-ball relation plays an important, if not decisive role in the control of interceptive actions, analysis of this relation would constitute a necessary element for understanding the control of action. Following the lead of Wagner (1982), Bootsma and Van Wieringen analyzed the player-ball relation by focusing on the evolution of the relative rate of dilation (RRD) of the (moving) ball's angular extent subtended at the (moving) point of observation. This variable corresponds to the inverse of the first-order time to contact between player and ball. Thus capturing the evolution over time of a particularly useful temporal relation between player and ball (see Bootsma et al., 1997), the analysis demonstrated that for each individual player this evolving relation was characterized by the occurrence of a minimum in between-trial variation. Rather than associating the instant of minimal variability in the temporal relation between player and ball with a decision to initiate a particular movement phase, Bootsma and Van Wieringen (1990) interpreted it as resulting from a continuous coupling between information and movement, thereby signing "*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" (p. 26). For their five top-level table tennis players this time interval was found to vary between 105 and 156 ms (mean $\pm$ *SD*: 121 $\pm$ 21 ms). These findings are thus fully compatible with Van Soest et al.'s assertion that the magnitude of the visuomotor delay ranges between 100 and 200 ms. As noticed by Bootsma and Van Wieringen, for two of their five players the visuomotor delay was 50 to 60 ms shorter than the duration of the movement, in principle allowing online corrections to be made.

In Van Soest et al.'s (2010) study, "*a minimum in the coefficient of variation of RRD during the drive was observed in none of the participants*" (p. 1045), again suggesting that their group was not of the same level of expertness as the participants of Bootsma and Van Wieringen's study. Interestingly, the same method of analysis was applied by Sardinha and Bootsma (1993) in a study of volleyball spiking, performed by five members of the Dutch national men's volleyball team that won the silver medal in the Barcelona Olympic Games of 1992. Each of these top-level volleyball players revealed a minimum in the coefficient of variation of RRD, corresponding to visuomotor delays of 138 $\pm$ 33 ms. Thus, a minimum in the coefficient of variation of RRD occurring between 100 and 200 ms before ball contact would seem to be the rule rather than the exception for top-level players.

Of course, one may question whether the moment of occurrence of the minimum in variability in the evolving first-order temporal relation between player and ball can be taken to sign the ultimate moment of control being possible. We note that this noninvasive method of estimating the duration of an individual's visuomotor delay gives rise to reasonable values, situating the visuomotor delay operating during the normal unfolding of action between 100 and 160 ms for top-level athletes. McLeod (1987) reported that top-level cricket players demonstrated changes in bat movement already 190 ms after an unexpected change in the ball's trajectory. Taking into account the amount of energy required to deviate a cricket bat from its current path of motion, it is clear that the visuomotor delays of these cricket players must also be situated within the range identified.

Conceptual Drifts in Operational Timing

According to Van Soest et al.'s (1994) initial suggestion, a particular muscle stimulation pattern "*molded by experience*" (p. 1400) is to be activated at the right moment in time, presumably on the basis of pertinent visual information. Van Soest et al. (2010) refer to this latter process as "operational timing" (p. 1040). In this section we examine the theoretical underpinnings and implications of this concept before demonstrating its inadequate evocation in Van Soest et al.'s conceptual framework in the next section.

Tyldesley and Whiting's (1975) Original Operational Timing Hypothesis

In line with the theoretical framework developed a few years earlier by Keele (1968), Tyldesley and Whiting (1975) interpreted their empirical observation of a very high degree of spatiotemporal consistency in the movement patterns of expert table tennis players performing attacking forehand drives as revealing the existence of

a motor program, firmly established after extensive practice. The originality of Tyldesley and Whiting's (1975) contribution resided in the suggestion that the consistency of movement execution effectively reduced the temporal uncertainty: Given that the movement will take a fixed amount of time, the player would only have to wait until the ball was a critical time away from the interception point before setting the program in operation. Thus the establishment of a consistent movement pattern was hypothesized to allow for what they coined operational timing.

Explicitly addressing the question whether the timing accuracy at movement onset was comparable to the timing accuracy at the end of the movement, Bootsma and Van Wieringen demonstrated that for each player studied the timing accuracy was better at the moment of ball-bat contact (3.1 ± 1.2 ms) than at movement onset (17.4 ± 7.9 ms). Movement duration itself had a variability of 11.7 ± 7.7 ms, also systematically larger than the observed terminal timing accuracy. From these findings, Bootsma and Van Wieringen (1990) concluded that "*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*" (p. 24).

Tresilian's (2005) Cognitive Version of Operational Timing

On several occasions Van Soest et al. (2010) refer to Tresilian's (1999, 2005) model of preprogrammed timing control as providing an adequate alternative interpretation of Bootsma and Van Wieringen's findings. In apprehending Tresilian's model, it is important to bear in mind that in Tyldesley and Whiting's (1975) perspective the duration of movement is a consequence of the execution of a motor program. Over their many years of practice, experts would have come to stabilize a supposedly limited number of motor programs, corresponding to the different drives in their repertoire. The duration affiliated with each of these motor programs would have been learned over practice, so as to allow for operational timing.

Tresilian (2005) takes a quite different stance, explicitly assuming that the duration of movement is planned, with desired movement time (*MT*) being an input to the movement plan: Not only does he argue that "*preprogrammed timing control involves producing a movement with a predetermined MT*" (p. 131), but also that "*MT can be preprogrammed to take different values*" (p. 132). In the presence of this remarkable ability to preprogram *MT*, operational timing is redefined by Tresilian (2005) as initiating the prepared program at a critical value of time-to-contact (TTC), defined for the occasion by the planned *MT* + Δ. The latter, Δ, is a (supposedly fixed) time span capturing the time delays for visual information to reach the motor control centers, for transmitting the motor command to the muscles and for the muscles to begin contracting in response to the command. Although Tresilian (2005) does not provide an estimate of Δ, taking the duration of a simple visual reaction time—requiring only the launching of a prepared response when the presence of a visual signal is detected— would appear to be reasonable within this information-processing

framework. This would place Δ on the order of 200 ms. The flow of events within Tresilian's scheme is thus the following. First, a movement of a chosen duration is planned, necessarily well in advance of action. Next, the critical value of TTC at which the program should be launched is determined on the basis of the chosen duration and the known Δ. When TTC reaches this freshly established critical value, the prepared program is launched. Movement begins Δ later and lasts *MT*, with the effector ideally arriving at the interception location at the same time as the moving target.

Tresilian (2005) developed this model of preprogrammed timing control to accommodate the finding that *MT* may vary over task conditions. Such findings lead proponents of a continuous coupling perspective to search for appropriate laws of control, describing the operative relations between informational and behavioral variables that explain the observed variations (e.g., Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994). Tresilian's (2005) preprogrammed timing perspective, on the other hand, a priori assumes that observed variations in *MT* are proactively planned, notwithstanding the nonunivocality of the mapping between central commands and movements produced already evoked by Bernstein (1967) over 50 years ago.

With *MT* actively varying over task conditions, Tresilian (2005) needed to introduce a supplementary step into his model to address Bootsma and Van Wieringen's findings of decreasing temporal variability under constant task conditions. To this end, Tresilian (2005) suggested that "*in constant task conditions, the programmed MT can vary due to changes from trial to trial in a person's internal state (e.g., motivation or fatigue)*" (p. 137). Thus, because of hypothetical fluctuations in internal state, on every repetition a *MT* slightly different from the average *MT* for the particular task conditions would be actively planned. With the critical value of TTC established each time anew as planned *MT* + Δ, a slightly longer *MT* program would be launched slightly earlier and a slightly shorter *MT* program would be launched slightly later. "*In other words, onset time variability is not just noise; it compensates for variations in MT_{prog} to ensure that strike time does not vary. Thus, far from being refuted by the observation that onset time variability is greater than strike time variability, the version of the operational timing described here can be considered to predict this result*" (Tresilian, 2005, p. 137). Such post hoc predictions based on putative adaptive processes endowed with *a priori* knowledge on *MT* seem little convincing to us. Moreover, the explanation proposed by Tresilian requires that planned variations in MT_{prog} supersede stochastic variations induced by internal noise. As internal noise sources may reasonably be estimated to influence the proposed perceptual and motor processes on the order of ±5% (Harris & Wolpert, 1998), a 200-ms MT_{prog} associated with a Δ of 200 ms would suffer from a stochastic variation of ±20 ms. Even with Δ set to 150 ms, the variability in movement duration observed over repeated trials in Bootsma and Van Wieringen's study amounts to only 3.9% of *MT* + Δ. Thus, the variability in the critical value of TTC that is assumed to compensate for variations in planned *MT* resulting from fluctuations in internal state is drowned in variability due to internal noise, clearly rendering inoperative Tresilian's (2005) allegedly "*adequate account of observed behavioral patterns and their intertrial variability, including Bootsma and van Wieringen's (1990) finding that vari-*

ability in movement onset time is greater than the variability of strike time over multiple trials" (Van Soest et al., 2010, p. 1041).

Musculoskeletal Dynamics and Timing of Stimulation

Van Soest et al.'s (1994, 2010) starting point was that the stabilizing visco-elastic properties of muscles might be expected to provide the mechanism underlying the phenomena observed by Bootsma and Van Wieringen (1990). Notwithstanding their otherwise surprisingly positive attitude towards the purely cognitive, disincarnated control scheme proposed by Tresilian (2005), Van Soest et al. (2010) argue that "*drive kinematics emerge from the interaction between the dynamics of the effector system and pre programmed muscle stimulation*" (p. 1051). Thus, in their perspective an observed movement pattern is not taken to directly reflect the commands issued by the CNS—as in central-dominance theoretical perspectives such as Tresilian's (2005) preprogrammed timing model or Schmidt's (1975) schema theory. Rather, an observed movement pattern is interpreted as resulting from the interplay between central commands (culminating in the muscle stimulation pattern) and the dynamical properties of the peripheral musculoskeletal effector system—as in central-guidance theoretical perspectives such as Bizzi, Hogan, Mussa-Ivaldi, and Giszter's (1992) equilibrium point model. While explosive movements of the type modeled by Van Soest et al. (1994, 2010) are suggested to require a pre-established stimulation pattern, the underlying theoretical perspective is one in which *MT* is not an input to a control plan, but rather a result emerging from the unfolding dynamics. The view of movement kinematics as emerging from dynamics is in our perspective the most plausible, the most promising and the most parsimonious. Examining the dynamics of information-movement coupling (see Bootsma, 1998), it has structured much of our work over the past years (e.g., Bootsma et al., 1997; Chardenon et al., 2004; Fernandez & Bootsma, 2008; Montagne et al., 1999; Mottet, Guiard, Ferrand, & Bootsma, 2001; Peper et al., 1994; Zaal, Bootsma, & Van Wieringen, 1998).

In the above-cited type of work, we address the dynamical relations between informational and behavioral variables, as captured by laws of control operating at the level of the agent–environment interaction (Warren, 2006). Referring to this level of analysis as "short-route modeling," Beek, Dessing, Peper, and Bullock (2003) have argued that such an analysis does not address the potentially control-shaping constraints provided by the dynamical properties of the sensory, neural and musculoskeletal subsystems of the agent performing the task at hand. Exploring the potentially structuring role of the visco-elastic properties of the musculoskeletal system in hitting actions, as proposed by Van Soest et al. (1994, 2010), is a clear example of the expected benefits of "long-route modeling" (Beek et al., 2003). While analysis at the level of information-movement coupling allows the (structure-independent) function subserved to be clearly captured, we agree that an understanding of the implementation of the identified "algorithm" requires "long-route modeling" (Bootsma, 1998). As long as the latter can avoid calling upon theoretically insufficiently founded components, we are sympathetic to this approach. Unfortunately—as is often the case in "long-route modeling" attempts—the simulations provided by Van Soest et al. (2010) for the forehand smash in table tennis suffer from the introduction of such a "ghost in the machine" component, with the

muscle stimulation program being launched at a theoretically unfounded moment in time, computationally optimized (and hence different) for each simulated drive. Van Soest et al. (2010) seek to justify this drive-by-drive timing optimization by referring to the operational timing concept. However, as should be clear from our foregoing discussion of this concept, operational timing consists in timing the initiation of movement on the basis of precise a priori knowledge of the upcoming movement's duration. Such precise a priori knowledge of movement duration (and other kinematics) is incompatible with the proposition of Van Soest et al. (1994, 2010) that the dynamical characteristics of the musculoskeletal system provide for a low-level mechanism whose online operation influences the evolution of the movement kinematics.

We certainly do not want to suggest that we do not believe that musculoskeletal dynamics participate in shaping movement characteristics. However, we argue that—because of the introduction of unprincipled variations in the timing of the onset of muscle stimulation—Van Soest et al.'s (2010) simulation study does not adequately test their specific hypothesis that the visco-elastic properties of muscles contribute to the "*kinematic convergence and related phenomena observed during table tennis drives*" (p. 1051). A proper test, unequivocally speaking to these issues, would require that for each individual trial, starting from a somewhat different initial configuration, the hypothesized single muscle stimulation pattern be launched at an identical moment in (perceivable) time to contact. As this procedure would appear to have failed to yield the desired results, Van Soest et al. (2010) introduce a confounding degree of freedom—acting as a ghost in the machine—by allowing a (computationally optimized) trial-to-trial variation in the time of launching of the muscle stimulation pattern. As a result, the movement characteristics emanating from the simulation study (as reported in Tables 7 to 9 and Figure 7 in Van Soest et al.) do not speak to the potentially structuring role of the musculoskeletal system, as they would seem to be critically dependent on the (unrelated) timing of muscle stimulation.

Adding a Layer of Model-Based Predictive Control

Even in the presence of the "ghost in the machine" degree of freedom discussed above, the postoptimization model simulations did not succeed in reproducing the richness of the characteristics of even a few trials of a single player's behavioral pattern.[2] Terminal timing accuracy remained an order of magnitude worse than experimentally observed, while the bat's rate of change of direction at the moment of ball-bat contact was both very variable and low as compared to the experimental data. Moreover, simulated movements did not reproduce the experimentally observed correlations between time-to-contact at movement initiation and acceleration during the drive, leading Van Soest et al. to suggest that "*the corrective adjustments of the arm movement suggested by these correlations are the outcome of model-based predictive control*" (p. 1052). Thus, while starting from the suggestion that the visco-elastic properties of the musculoskeletal system could explain the phenomena described by Bootsma and Van Wieringen (1990), the

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[2] The simulation was restrained to six selected drives of a single participant, notwithstanding the availability of data for a total of 347 drives for the seven participants.

behavioral patterns observed lead Van Soest et al. (2010) first to add a nontheoretically founded degree of freedom (allowing for trial-to-trial variations in timing the onset of muscle stimulation) and second to add a supplementary layer of model-based predictive control. It is, at least to us, hard to see how this elaborate and conceptually tottering final scheme—in clear contradiction with the repeated arguments of Van Soest et al. (1994) in favor of a simple control architecture—can be put forward as a viable and more appropriate alternative to the parsimonious information-based control architecture proposed by Bootsma and Van Wieringen and further elaborated since.

Conclusion

Van Soest et al.'s (2010) experimental and simulation studies suffer from a considerable number of methodological and conceptual shortcomings. Vision was removed shortly after movement initiation, rather than one visuomotor delay before movement initiation, as a true test of their hypothesis would necessitate. The global suppression technique consisting of bluntly removing vision (rather than manipulating relevant optical variables) is likely to have influenced the operative control processes. Participants were of a lesser level of expertness than those studied by Bootsma and Van Wieringen (1990), compromising the possibility to reproduce the observation of online regulations because of lesser consistency and longer visuomotor delays. Simulations did not allow the structuring effects of the dynamics of the musculoskeletal system to be identified, as these were confounded with the effects of (unprincipled) variations in timing the onset of muscle stimulation. Notwithstanding the fact that the simulation study was based on only a few trials of a single participant, it still did not succeed in capturing the richness of the behavioral patterns observed. The step of invoking a supplementary control layer certainly does not contribute to conceptual clarification or parsimony of the account proposed.

It is thus clear that Van Soest et al.'s (2010) experimental study remains far from providing a convincing demonstration that top-level players cannot visually regulate their interceptive actions as suggested by Bootsma and Van Wieringen (1990). Within the same framework, it is also clear that Van Soest et al.'s (2010) simulation study does not provide convincing arguments in favor of a coherent and parsimonious alternative to the continuous information-movement coupling perspective proposed by Bootsma and Van Wieringen (1990). Thus, however deranging Bootsma and Van Wieringen's conclusions might appear to be to some, there is still, 20 years later, no sufficient reason to reject them. Undoubtedly much work remains to be done to arrive at a full understanding of perceptuomotor control in rapid interceptive actions. We suggest that such work should start from Bootsma and Van Wieringen's bottom-line position that the (perhaps task-specific) duration of an individual's visuomotor delay determines the ultimate moment of control being possible.

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