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Reorganization of Catching Coordination Under Varying Temporal Constraints

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In the present study, the limits of human catching behavior were challenged to investigate quantitative and qualitative adaptations of the catching movement when performing under varying ball speeds, implying minor as well as severe temporal constraints. Nine male participants caught balls approaching at speeds ranging from 8.5 to 19.7 m/s with their preferred hand. Although a decrease in catching performance was undeniable, several quantitative adaptations provided the catcher with extra time and allowed to compensate the decrease in spatial accuracy with increasing speed. More importantly, changes in the coordination between hand, elbow, and shoulder emerged with increasing movement velocity. More demanding temporal constraints lead to a shift from relatively independent activity of each joint towards a mode in which several joints act as one unit. This reorganization of the coordination pattern of the catch is discussed in the context of Bernstein's degrees of freedom problem.

Key Words: one-handed catching, temporal constraints, coordination, kinematics

In spite of the relevance of catching in both daily activities and sports performance, only few mechanisms or strategies that address the question how the human perceptuo-motor system deals with changing temporal constraints have been identified. Such mechanisms were mainly derived from simple, low-dimensional interception tasks (e.g., Tresilian, 2004), but have not been thoroughly explored in natural catching. Laurent, Montagne, and Savelsbergh (1994) already showed that several discrete qualitative changes in the catching movement appeared to meet the temporal constraints, such as a backward shift of the interception point (place of ball–hand contact) and an increase in the straightness of the trajectory of the wrist. In self-paced prehension tasks, in which participants reached for a stationary object, additional adaptations to temporal constraints were found. The occurrence of a larger peak hand aperture in faster reaching movements was

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considered as a compensating mechanism for the decrease in spatial accuracy that is commonly observed when movement speed increases (Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Fitts, 1954; Watson & Jakobson, 1997; Wing, Turton, & Fraser, 1986).

However, intra-limb coordination profiles and changes therein when catching under changing temporal constraints remain relatively undocumented. The human perceptuo-motor system might deal with these changes in several ways. A quantitative option would be to speed up the movement execution while retaining the general temporal and spatial structure of the movement (Maraj, Elliott, Lee, & Pollock, 1993; Schmidt, 1985). However, Laurent et al. (1994) already showed that speeding up the catch did not involve a general scaling of the movement. An alternative solution might be to qualitatively change the movement pattern in function of the task constraints. As temporal constraints increase, the motor system will try to reduce its number of degrees of freedom involved, to still produce and control extreme high-speed catching successfully. Initially, the degrees of freedom (DOF) problem was put forward by Bernstein (1967), and was situated in the field of skill acquisition and motor learning. His theoretical framework proposed two strategies to deal with the restriction of the DOF to a controllable portion. First, a reduction of DOF can be obtained by "rigidly and spastically fixing" or freezing joint articulations, a strategy that is usually adopted when subjects are faced with a new skill (McDonald, van Emmerik, & Newell, 1989; Newell & van Emmerik, 1989; Vereijken, van Emmerik, Whiting, & Newell, 1992). Later in the learning process, the motor system copes with the redundant DOF by introducing "temporarily strong, rigid couplings between multiple degrees of freedom" or "coordinative structures" (Davids, Glazier, Araújo, & Bartlett, 2003; Turvey, 1990). This can be accomplished, for example, by moving two or more joint complexes in close phase relations. A commonly used technique to investigate these time-relationships between components of the moving system is by determining cross-correlations among time series (Amblard, Assaiante, Lekhel, & Marchand, 1994; Ko, Challis, & Newell, 2003; Lees, 2002; McDonald et al., 1989; Temprado, Della-Grasta, Farrell, & Laurent, 1997; Vereijken et al., 1992).

The main purpose of the present experiment was to investigate how the motor system deals with a wide range of varying temporal constraints in one-handed catching. The first issue to be addressed is defining the temporal limits within which the human motor system is still capable of producing a movement that meets the spatial and temporal requisites. Next to this behavioral issue, the question arises how the human perceptuo-motor system successfully adapts to these imposed temporal constraints. Therefore, changes in coordination between the shoulder, elbow, and hand during catching under increasing temporal constraints were explored. From a Bernsteinian perspective, it can be hypothesized that increasing temporal constraints would entail an introduction of coordinative structures to reduce DOFs. In addition, the changes in timing and movement accuracy as reported by Laurent et al. (1994) are expected to be confirmed and elaborated within a broader range of temporal constraints.

Methods

Participants

Since the limits of human catching performance were explored in the present study, volunteering candidate participants were put through a demanding screening test. In a one-handed ball catching task at a speed of 14.5 m/s, they had to catch at least 23 out of 25 balls, i.e., over 90%. Possible interference due to visual limitations was excluded by screening the participants' visual capacities as well. Therefore, stereo acuity and visual acuity were checked after passing the catching test. "Normal" stereo acuity scores of 40 s of arc or better, as measured with the Graded Circle Test (from the "Random Dot Stereo Butterfly" test battery; Stereo Optical Co., Inc., Chicago, IL), and accurate visual acuity of 1.00 assessed using the "Snellen E chart" were required. Finally, nine right-handed male participants ranging in age from 18 to 22 years with normal or corrected-to-normal vision were selected to take part in the experiment. All participants were informed about the experimental task, but were naive to the purpose of the experiment. Before testing, they gave their written consent to participate. The study was approved by the Ethics Committee of the Ghent University Hospital.

Task and Apparatus

As in the selection test, yellow mid-pressure tennis balls were projected towards the participant by a Singly Promatch ball projection machine (Promatch/Mubo B.V., Gorinchem, The Netherlands) with adjustable launching speed and angle. The participants stood in a comfortable starting position with both arms and hands relaxed beside the body, the right foot placed on a mark on the floor.

Balls were launched from a distance of 8.4 m from the participant's frontal plane at seven different speeds ranging from 8.6 m/s to 19.7 m/s, resulting in flight times of the ball of 976 ms to 426 ms, respectively (see Table 1). The launching angle of the ball machine was adjusted for every ball speed and body height of the participant, so that all balls would arrive in an imaginary circle (30 cm in diameter) with its center approximately 15 cm above the shoulder of the catching arm.

The catching movement was tracked with a 240 Hz 3D motion capturing system (Qualisys, Gothenburg, Sweden). Six infra-red cameras captured the movement of 10 reflective markers (7 mm in diameter) that were attached with double-sided adhesive cloth tape to the processus coracoideus of the scapula, processus coronoideus of the humerus, processus styloideus of radius and ulna, caput metacarpal and external face of the distal phalanx of thumb, index, and little finger of the catching arm and hand.

Table 1 Mean Ball Speeds (in m/s) and Corresponding Flight Times of the Ball to Reach the Catcher's Frontal Plane (in ms) for Each of the Used Temporal Constraint Conditions

Ball speed (m/s)	8.6	10.6	12.5	14.5	16.4	18.0	19.7
Flight time (ms)	975.6	790.6	673.8	581.2	512.9	467.3	425.8

Procedure

Participants attempted to catch balls in blocks of 20 trials at each of the seven speeds with their preferred hand. For safety reasons, the blocks were presented in a fixed order starting from the lowest and increasing to the highest ball speed. Five acclimatization trials were provided to adapt to the new ball speed and to check the launching angle of the ball machine. Before a ball was launched a "ready" signal was given. In case the ball was caught, the participant dropped the ball into a basket on his right-hand side and then returned to his original starting position. If not, the starting position was adopted at once. After each trial, one of the experimenters scored the overall catching performance as a catch, touch, or miss. Participants wore earphones to minimize the noise of the launching machine and hence exclude anticipatory behavior on the sound of the ball as it fell into the launching mechanism. However, participants could anticipate to some extent, as the ball was visible an instant before it was launched. This interval, while the ball was handled by the launching mechanism, was identical for all ball speeds and lasted 17 ms (± 3 ms).

Data Analysis and Dependent Measures

The number of successful catches was used as a measure of the overall catching performance. To sort out how the motor system adjusted to the imposed temporal constraints, only data of successful trials (six in each speed condition for all participants) were included into the kinematic analysis. Failures were deliberately excluded from the analysis because the goal was to find out how the catcher adapts successfully to the imposed temporal constraints. In addition, statistical comparison of kinematical data of successful catches and failures was problematic due to a lack of catching failures at the lower ball velocities.

Before extracting kinematic variables, the moment of ball-hand contact was derived from the 3D visual reconstruction of the catching movement in the Qualisys software program. The impact of the ball on the hand was clearly visible as a sudden backward jerky movement of the metacarpal and finger markers. Then these 3D data were converted into time series of x, y, and z coordinates for each marker, which were filtered at a cut-off frequency of 10 Hz with a second-order recursive Butterworth filter. Subsequently, velocity of the wrist and joint angles were computed from these positional data. Finally, the required variables could be determined. All temporal variables were defined with respect to ball-hand contact.

The kinematic variables that were considered were classified into two clusters. A first group of discrete variables reflects the temporal structure and aspects related to, respectively, the transport and manipulation phase of the catch. The second cluster contains variables that represent intra-limb coordination.

Timing and Accuracy Variables

- Movement time (MT, in milliseconds): time elapsing from the onset of the first wrist movement until ball-hand contact. The criterion used for movement initiation was the moment that wrist acceleration grew larger than 300 mm/s^2.
- Latency time (LT, in milliseconds): time elapsing between the departure of the ball at the ball machine and the first hand movement, calculated as flight time

of the ball minus the time that the flight time was reduced due to the forward displacement of the ball-hand contact, minus the movement time.

- Grasping time (GT, in milliseconds): time elapsing from the moment the hand opening velocity turns negative after reaching maximal hand aperture, until ball-hand contact.
- Acceleration-Deceleration Ratio (AD ratio): the ratio between duration of acceleration and deceleration phase. The moment of occurrence of maximal instantaneous velocity of the wrist from initiation of the movement until contact was used to distinguish acceleration and deceleration phase (in accordance with Laurent et al., 1994; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). Hence, acceleration and deceleration phase were defined as the time from movement onset to the time of peak wrist velocity and time from occurrence of peak wrist velocity until ball-hand contact, respectively.
- Coefficient of Straightness (CoS, in percent): the traveled path of the wrist divided by the distance of the shortest linear path × 100, specifying the rectilinearity of the wrist trajectory. Note that this variable is the inverse of the coefficient of straightness defined by Laurent et al. (1994), i.e., shortest path divided by real path × 100.
- Forward displacement of the wrist/elbow/shoulder (DxW/DxE/DxS, in millimeters): linear distance between the position of, respectively, the wrist, elbow, and shoulder at the initiation of the catching movement and ball-hand contact along the anterior-posterior axis (x-axis).
- Peak Hand Aperture (PHa, in millimeters): the maximal linear distance obtained between the thumb and index finger during the catching movement.

Coordination Variables

- Cross-correlation between transport and manipulation (CCTM): this is the cross-correlation between time series of wrist velocity and hand aperture, representing, respectively, the transport and the manipulation component of the catch.
- Cross-correlation between 3D angles of elbow and hand (CCEH): the cross-correlation expresses how the two angles evolve in time against one another. The elbow angle is defined as the angle that arises between the markers of, respectively, processus styloideus ulnaris, processus coroideus humeri, and processus coracoideus scapularis. The hand angle represents hand aperture: the angle between the external face of the distal phalanx of the index, processus styloideus radialis, and the external face of the distal phalanx of the pollex.
- Cross-correlation between 3D angles of shoulder and hand (CCSH): the shoulder angle is the angle that subtends the humerus (from the processus coroideus humeri to processus coracoideus scapularis) and the torso (line between the processus coracoideus scapularis and a virtual marker created by vertically translating the marker of the processus coracoideus scapularis).
- Cross-correlation between 3D angles of elbow and shoulder (CCES): both angles defined as described previously.

Cross-correlation coefficients with zero time lag were calculated to analyze the coordination pattern between shoulder, elbow, and hand. The absolute value of the coefficient represents the strength of the coupling. A cross-correlation coefficient nearer to 1 represents a closer linkage, whereas a coefficient approximating zero signifies that joints move more independently from one another (Ko et al. 2003; Temprado et al. 1997; Vereijken et al. 1992). The sign indicates the direction of the changes: positive coefficients represent changes in the same direction, while negative values indicate that both joints change in opposite directions. Cross-correlation values were first determined for each separate trial, and then averaged per participant for each ball speed condition. These mean cross-correlations were submitted to a repeated measures ANOVA to quantify possible changes in coordination pattern. In addition, intra-subject standard deviation was calculated for the joint coordination variables CCEH, CCSH, and CCES, to assess the variability of the implemented movement pattern.

Statistical Analysis

Analysis of variance with repeated measures on the factor speed was carried out on the performance scores and kinematic variables. Post hoc comparisons were conducted with the LSD test to examine the nature of the main effects. An alpha level of .05 was used for all statistical tests and the size of the effect was evaluated by means of the partial Eta squared (η_p^2).

Results

With respect to overall catching performance, a main speed effect was found (see Table 2). As ball speed increased, catching performance decreased, $F(6, 48) = 26.105$, $p < .001$, $\eta_p^2 = .765$. Note that in the highest ball speed condition more than 50% of all trials were still caught.

Timing and Accuracy Analysis

Movement time decreased as the ball approached faster, $F(6, 48) = 313.019$, $p < .001$, $\eta_p^2 = .975$. Significant differences occurred between all speed conditions. A similar speed effect was also present for latency time, $F(6, 48) = 5.330$, $p < .001$, $\eta_p^2 = .400$. Post hoc analysis revealed no differences in latency time for the lower ball speeds: for ball speeds 8.6 m/s, 10.6 m/s, and 12.5 m/s latency times approximating 140 ms were recorded. When ball speed exceeded 12.5 m/s latency times decreased progressively from 119 to 80 ms for ball speeds from 14.5 to 19.7 m/s. For grasping time no effects were found, $F(6, 48) = 1.672$, *ns*, $\eta_p^2 = .173$, meaning that the grasp was initiated at a constant time prior to contact regardless of the speed of the ball.

The ratio between the duration of acceleration and deceleration phase increased with increasing temporal constraints, $F(6, 48) = 15.872$, $p < .001$, $\eta_p^2 = .665$. More specifically, the relative contribution of the deceleration phase in the total movement time decreased as the temporal window declines. Analysis of the coefficient of straightness indicated that when temporal constraints increased, the wrist moved in a more rectilinear way to the place of interception, $F(6, 48) = 5.309$, $p < .001$, $\eta_p^2 = .399$. As ball speed increased, wrist and elbow were located closer to the body

Table 2 Catching Performance and Variables Representing the Timing and Accuracy of the Catching Movement Under Changing Temporal Constraints

	Ball speed condition (m/s)						
	8.6	**10.6**	**12.5**	**14.5**	**16.4**	**18.0**	**19.7**
Catch perf							
Mean	20.0	19.9	18.4	17.3	15.3	13.3	11.4
SD	0.0	0.3	1.5	2.5	3.0	3.8	2.6
MT*							
Mean	808.3	618.2	512.1	444.8	392.4	354.7	335.2
SD	72.3	35.9	32.3	26.4	25.1	17.2	25.3
LT*							
Mean	133.4	141.3	137.9	118.8	105.7	100.0	79.8
SD	73.0	40.1	35.2	29.7	27.2	18.2	24.5
GT							
Mean	59.7	51.5	50.5	49.7	50.8	51.5	51.7
SD	21.1	7.5	10.9	9.7	9.9	10.3	10.7
AD ratio							
Mean	0.81	0.89	1.00	1.22	1.29	1.40	1.73
SD	0.22	0.22	0.14	0.18	0.16	0.30	0.62
CoS							
Mean	111.2	107.6	106.3	106.3	105.8	105.9	105.5
SD	4.8	4.2	2.8	3.9	2.3	2.2	2.4
DxW							
Mean	291.6	327.0	297.4	254.8	243.9	226.2	213.4
SD	91.2	89.8	83.7	94.5	85.1	71.1	82.5
DxE							
Mean	278.6	293.4	258.9	220.2	204.9	181.1	185.4
SD	62.7	61.0	59.7	85.2	72.4	53.6	54.7
DxS							
Mean	–10.5	1.1	–9.8	–41.0	–46.8	–51.6	–62.5
SD	62.7	61.0	59.7	85.2	72.4	53.6	54.7
PHa							
Mean	116.0	120.8	123.5	125.9	125.7	126.7	129.6
SD	10.9	12.2	11.3	11.3	9.0	11.1	11.6

Note. Means and standard deviations of catching performance (Catch perf., as number of successful trials out of 20), movement time (MT, in ms), latency time (LT, in ms), grasping time (GT, in ms), acceleration-deceleration ratio (AD ratio), coefficient of straightness (CoS, in percent), forward displacement of, respectively, the wrist, elbow, and shoulder (DxW, DxE, DxS; in mm) and peak hand aperture (PHa, in mm) are given for the seven ball speed conditions. *The sum of MT and LT is always lower than the theoretical flight times (see Methods section) since the ball is caught in front of the catcher's frontal plane. Extending the arm forward towards the interception point reduced real flight times with 34 to 11 ms for the lowest and highest ball speed, respectively.

at the moment of ball-hand contact, $F(6, 48) = 8.740$, $p < .001$, $\eta_p^2 = .522$ and $F(6, 48) = 12.981$, $p < .001$, $\eta_p^2 = .619$; for wrist and elbow, respectively. The shoulder even showed a backward displacement: it was more and more withdrawn with increasing ball speed, $F(6, 48) = 9.702$, $p < .001$, $\eta_p^2 = .548$. Finally, increasing ball speed elicited a larger hand opening before the initiation of the grasp, $F(6, 48) = 8.769$, $p < .001$, $\eta_p^2 = .523$.

Analysis of Movement Coordination

Before looking more closely at the coordination of the catching arm and hand, plots representing changes in angle of hand, elbow, and shoulder are shown in Figure 1. These plots reflect how each of these joints evolves separately through time while a successful catch is in progress. These figures visualize several of the previously reported speed effects. A decrease in movement time can be clearly observed in each of the figures. Figure 1a shows that opening the hand takes less time, while the grasp itself does not vary with increasing time constraints. The higher peak hand apertures with increasing ball speed are displayed as well. Exploring elbow movement (Figure 1b), a longer extension phase of the elbow preceding contact is present for the lower ball speeds. Maximal elbow flexion increases and occurs closer to contact when temporal constraints increase. This results in a more flexed configuration of the elbow at moment of ball-hand contact with increasing ball speed. As for the contribution of the shoulder in the transport of the hand to the point of interception, a remarkable decrease of shoulder angle amplitude occurs with increasing temporal constraints (see Figure 1c).

At the coordination level, the relationship between transport and manipulation phase was analyzed by determining the cross-correlations among times series of wrist velocity and hand aperture. Repeated measures analysis on the mean cross-correlation values revealed a strong speed effect, $F(6, 48) = 21.778$, $p < .001$, $\eta_p^2 = .731$. With increasing ball speed, CCTM increased from .05 to .80 for the 8.6 to 19.7 m/s condition, respectively. At the lowest ball speeds, the hand is moved towards the appropriate point in space (transport) followed by the opening and closing of the hand (manipulation). When the temporal window declines, both transport and manipulation are executed more and more concurrently. To investigate intra-limb coordination in catching more profoundly, cross-correlations were calculated between time series of, respectively, elbow versus hand angle, shoulder versus hand angle, and elbow versus shoulder angle. Statistical analysis revealed that CCEH increased with increasing temporal constraints, i.e., when ball speed increased, both elbow flexion and hand extension occurred more simultaneously, $F(6, 48) = 6.915$, $p < .001$, $\eta_p^2 = .464$. For CCSH, a speed effect was present as well, $F(6, 48) = 7.259$, $p < .001$, $\eta_p^2 = .476$). However, the shoulder-hand coordination appeared to be inverse compared to the elbow-hand coordination: CCSH decreased with increasing temporal constraints. To put it differently, shoulder and hand movements disconnect more and more as ball speed increased. LSD post hoc tests, however, showed only significant differences between the higher ball speed conditions. Coordination patterns between shoulder and hand were found to be similar for ball speeds ranging from 8.6 m/s to 14.5 m/s (see Table 3). Finally, CCES did not vary with changing temporal constraints, $F(6, 48) = .493$, *ns*, $\eta_p^2 = .058$.

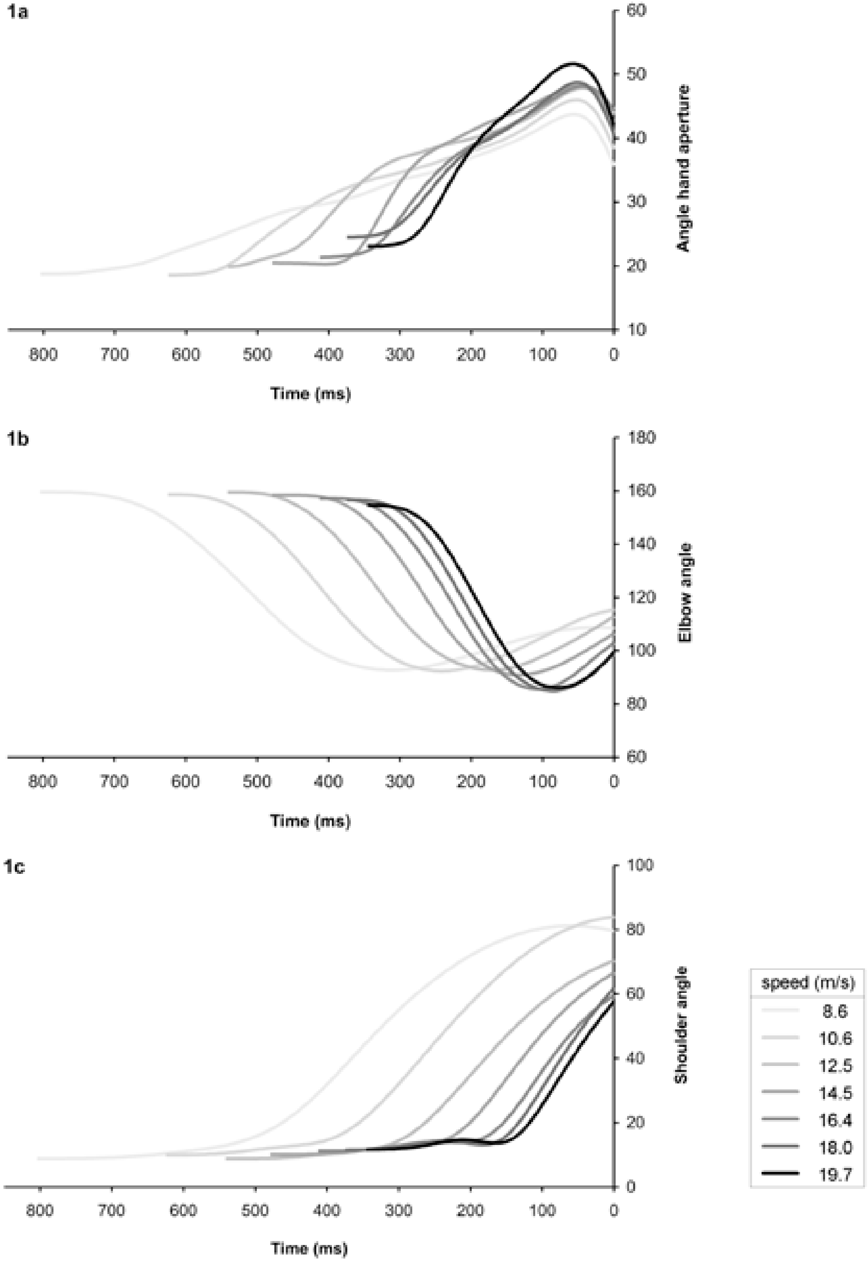

Figure 1—Time series of angles of hand (1a), elbow (1b), and shoulder (1c). Angles are expressed in degrees. These figures are derived from data from one typical participant. Means of six successful trials at each speed condition were plotted against time. The zero on the time axis represents ball-hand contact.

Table 3 Means and Standard Deviations of the Cross-Correlation Variables Under Varying Temporal Constraints

	Ball speed condition (m/s)						
	8.6	10.6	12.5	14.5	16.4	18.0	19.7
Cross-corr transport-manipulation							
Mean	.05	.23	.37	.53	.58	.67	.80
SD	.33	.36	.34	.30	.28	.28	.12
Cross-corr elbow-hand							
Mean	–.69	–.76	–.84	–.87	–.91	–.90	–.92
SD	.23	.19	.12	.10	.06	.05	.05
Cross-corr shoulder-hand							
Mean	.82	.84	.85	.82	.77	.69	.66
SD	.13	.13	.12	.09	.12	.18	.17
Cross-corr elbow-shoulder							
Mean	–.77	–.76	–.79	–.77	–.77	–.77	–.76
SD	.10	.11	.09	.10	.07	.06	.06

Angle-angle plots from time normalized and averaged trials of all participants for each ball speed condition allow visualization of these effects on intra-limb coordination (Figure 2). Figure 2a represents the elbow-hand coordination; i.e., how are elbow and hand aperture related during the progression of the catch? At the lower ball speeds, two more distinct phases are clearly present up to peak hand aperture. First, elbow flexion is mainly executed (transport phase), followed by the main action of the hand (manipulation phase). For the higher ball speeds, both actions are executed more simultaneously, which results in a closer coupling between elbow and hand movements. For the shoulder-hand coordination, an inverse effect can be derived from Figure 2b. When temporal constraints increase, a wider hand aperture will be reached before any shoulder movement occurs. Notice also the smaller range of shoulder movement at the higher speed conditions. In Figure 2c, the close resemblance of elbow versus shoulder movement over all speed conditions is striking. The elbow movement is clearly preceding shoulder movement. This indicates that the hand moves to the ball by first flexing mainly the elbow, followed by a shoulder extension that raises the hand further while the elbow is kept more or less at the same angle. This coordination pattern holds irrespective of ball speed.

Analysis of intra-subject variability revealed similar effects as was found in the cross-correlation analysis (see Table 4). Variability on CCEH decreased with increasing temporal constraints, $F(6, 48) = 5.612$, $p < .001$, $\eta_p^2 = .412$, indicating a more consistent movement pattern when catching under increasing temporal constraints. Coordination between shoulder and hand, however, showed a larger within-subject variability with increasing ball speed, $F(6, 48) = 2.328$, $p < .05$, $\eta_p^2 = .225$. For elbow-shoulder coordination, no speed effect on intra-subject variability was present, $F(6, 48) = 1.039$, *ns*, $\eta_p^2 = .103$.

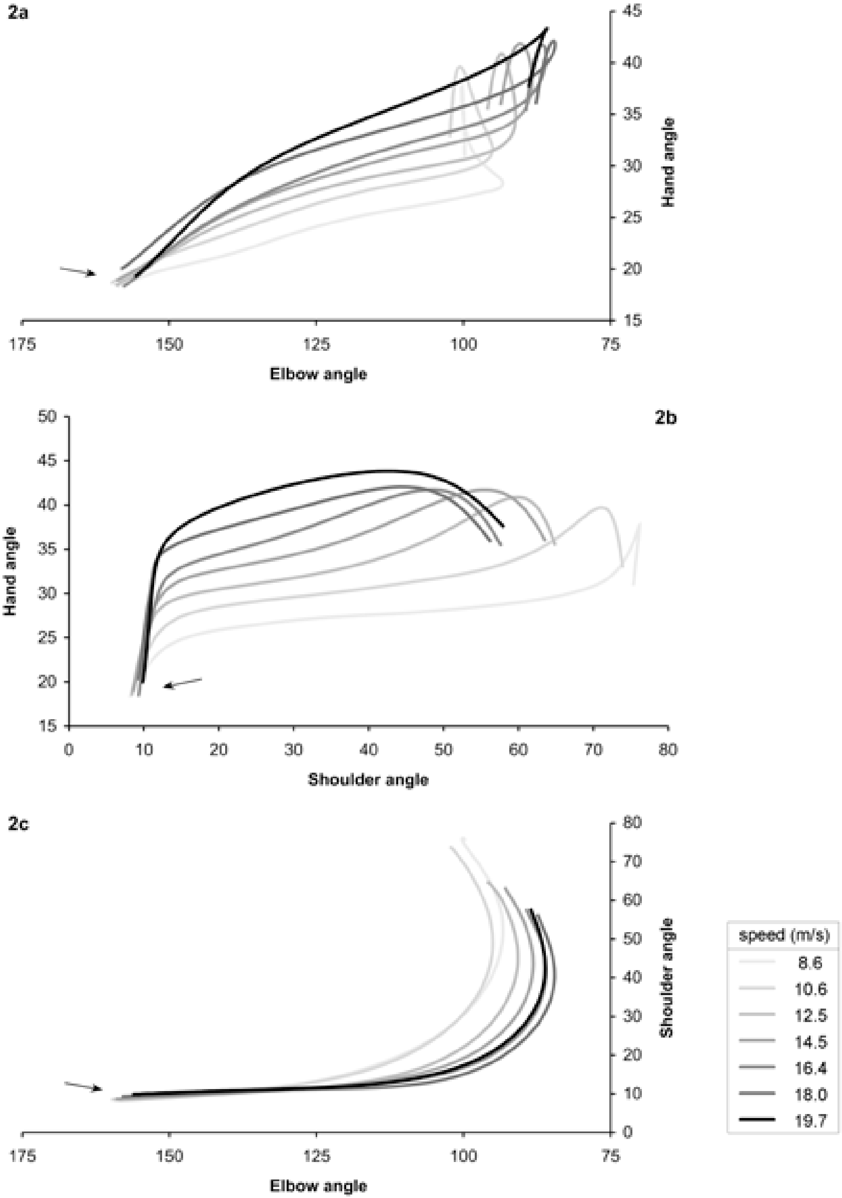

Figure 2—Angle-angle plots of time series of elbow against hand angle (2a), shoulder against hand angle (2b), and elbow against shoulder angle (2c) for all speed conditions (angles are expressed in degrees; the hand angle represents the angle of hand aperture). These figures display mean data from all participants. Data from six successful trials for each speed condition and each participant were normalized in time and subsequently averaged. The arrow indicates movement initiation.

Table 4 Intra-Subject Variability for the Cross-Correlation Coefficients Between Elbow-Hand, Shoulder-Hand, and Elbow-Shoulder Under Varying Temporal Constraints

	Ball speed condition (m/s)						
	8.6	10.6	12.5	14.5	16.4	18.0	19.7
Cross-corr elbow-hand							
Mean	.109	.107	.057	.045	.052	.043	.028
SD	.078	.084	.041	.040	.048	.032	.025
Cross-corr shoulder-hand							
Mean	.064	.067	.058	.059	.091	.083	.089
SD	.031	.041	.036	.038	.042	.060	.036
Cross-corr elbow-shoulder							
Mean	.051	.047	.039	.041	.039	.037	.041
SD	.022	.024	.020	.018	.017	.017	.020

Discussion

The aim of the present study was to address the reorganization of the catching movement due to temporal constraints, pushing the perceptuo-motor system to its limits. With increasing ball speed, adaptations were not solely present in discrete measures of transport and manipulation but in the intra-limb coordination pattern as well. Adaptations in timing and movement accuracy to the varying temporal constraints will be briefly discussed, followed by an elaboration on the changes in intra-limb coordination.

Timing and Accuracy

To summarize the results regarding the temporal structure of the catch, a decline in both LT and MT was found, while grasping time remained unaltered when the temporal window decreased. In contrast with Laurent et al. (1994), our subjects initiated their movements earlier as the temporal window decreased. Since LTs in our study were equivalent to those reported in the Laurent et al. (1994) study at the corresponding ball velocities, it is possible that with increasing the ball speed in the experiment of Laurent et al. (1994) further, shorter LTs would have appeared as well. Another remarkable finding is that the grasp was initiated at a constant time before ball-hand contact irrespective of ball speed, which confirms the use of a constant ttc strategy for the timing of the grasp (Laurent et al., 1994; Mazyn, Lenoir, Montagne, & Savelsbergh, 2004; Savelsbergh, Whiting, Burden, & Bartlett, 1992).

Examining the velocity profile of the catch, the AD ratio clearly demonstrates that the speeding up of the catch is not achieved by a simple scaling of the global movement, confirming the suggestions made by Laurent et al. (1994). However, next to a decrease in duration of the deceleration phase, which corroborates the findings of Laurent et al. (1994), a reducing acceleration phase was found as well (Figure 3). This shift from an asymmetric towards a symmetric velocity profile and back again as temporal constraints increase is in line with earlier observations of Wallace and Weeks (1988) in prehension movements. Again, it is likely that expanding the range of velocities used by Laurent et al. (1994) would entail similar changes in acceleration. As it is easier to actualize adaptations when movement velocity is lower (Jeannerod, 1988; MacKenzie et al., 1987; Marteniuk et al., 1987), an extended deceleration phase enables the catcher to correct the movement and adjust it precisely to meet the requisites of the task. Conversely, the fact that time for implementing corrections is barely available could explain the decline in catching performance when the temporal window is considerably reduced.

Laurent et al. (1994) also introduced two "time buying strategies" to deal with the temporal constraints in high-speed ball catching. First, their "retreat" of the interception point was confirmed in the present study. The data presented here show that this retreat is achieved at various levels. The retreat of the interception point is realized not solely by the wrist, but by a backward shift of the entire catching arm and shoulder. Since the catcher was not allowed to move his feet while catching, stepping backward was not an option to buy extra time. Therefore, the retreat of the shoulder had to be generated by a slight rotation or backward leaning of the trunk. From a witness camera that recorded the participants laterally, hardly any movement of the trunk could be observed. At the highest ball speed, the retreat of the interception point by 158.6 mm, compared to the slowest speed condition, extends the time available to accomplish the catch by 8 ms or 2.4%. Initially, this gain seems rather negligible. The observation that this meticulous adaptation is consistently repeated in all trials emphasizes the fine and subtle tuning of the movement to the changing environmental constraints. Second, the increase in

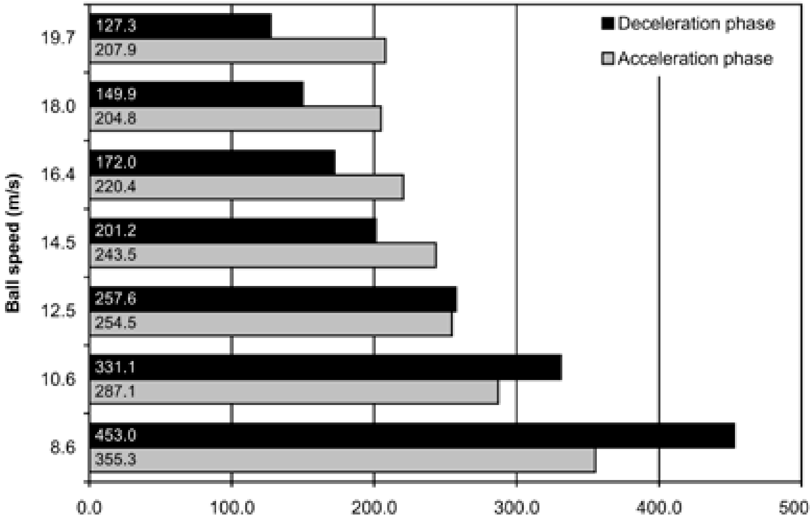

Figure 3—Durations of acceleration and deceleration phases of the transport component.

straightness of the trajectory of the wrist to deal with increasing temporal constraints was confirmed as well: a similar increase in rectilinearity was present, although a ceiling effect was found for ball speeds from 12.5 m/s and above. Furthermore, the present results provide evidence for an additional mechanism that compensates for a decrease in spatial accuracy. The catcher responds to the changing temporal constraints of the task by making the contact surface of the hand larger as the time available decreases. This finding translates the results of Wing et al. (1986) and Wallace, Weeks, and Kelso (1990) in a prehension task to unconstrained catching, thereby underlining the speed-accuracy trade-off of Fitts (1954). Analogous with the retreat of the interception point and the more rectilinear (i.e., shorter and hence less time-consuming) trajectory of the wrist which provides the catcher extra time (Laurent et al., 1994), one could say that this mechanism allows the catcher to buy extra space as well.

Coordination

So far, these results show that the catcher's response to increasing temporal constraints is not a general scaling of the catch, but involves a significant reorganization of the movement. Cross-correlation values between time series of wrist velocity and hand aperture (CCTM) approximating zero at the lowest ball speed, underline the phased movement execution when temporal constraints are low: first the transport takes place, followed by the manipulation phase with the wrist more or less stationary at the interception point. The faster the movement is performed, the more these two phases are executed concurrently.

A simplified model of the catching limb consists of three joint angles: shoulder, elbow, and hand (conducting a tweezers function), each extending and reducing in time. The most important adaptation to the imposed temporal constraints was situated at the level of elbow-hand coordination. When there was adequate time to make the catch, both the elbow joint and pincer function of the hand tend to act independently from each other. As the time window became more limited, both phases were executed more simultaneously as reflected by the higher cross-correlations. More proximally, the coordination pattern between elbow and shoulder did not show significant changes under varying temporal constraints. Regardless of temporal constraint, an initial isolated elbow flexion is followed by a simultaneous elbow flexion and shoulder extension and finally emerges to a more or less isolated shoulder extension. Shoulder and elbow appear to be organized according to a rigid pattern, imposed by the physical characteristics of the arm. From a biomechanical point of view, the mechanically most favorable way to raise the hand consists in an elbow flexion, followed by shoulder extension only at a later stage if the hand must travel farther upwards. This movement strategy reduces the moment of inertia of the arm to a minimum (Winter, 1990). At the level of shoulder-hand coordination an apparently strange effect was obtained: when temporal constraints increased, a disconnection of both components was present, i.e., a decrease in cross-correlation values. Closer inspection of the angle-angle plots in Figure 2 leads to a plausible explanation for this finding. When the ball approaches at a slower pace, first the elbow flexes followed by the simultaneous contribution of shoulder and hand. This concurrence of both hand and shoulder extension explains the higher cross-correlations between shoulder and hand angle at the low ball speed conditions. As the temporal constraints increase, the hand opens faster (see Figure 1a, the steeper course in the first part of the evolution of the hand angle in time) and hence moves more simultaneously with the elbow. Relative to the hand, the shoulder starts later as was the case in the lower speed conditions: larger amplitude of the hand angle has already been accomplished before any shoulder movement is present. An additional explanation for the decrease in cross-correlations between shoulder and hand angle with increasing temporal constraints might lay in the change in movement amplitude of both joints. As hand aperture increases with increasing temporal constraints, the range of shoulder motion decreases. Put differently, the lower cross-correlations could express the relative freezing of the shoulder joint. Figure 1c illustrates that when the temporal constraints increase, the role played by the shoulder becomes rather limited: the joint is only involved in the last 100 ms. In this way, the catcher could adapt to the increasing constraints by moving the hand as a functional unit (coupling) with the elbow and by freezing the shoulder joint at the same time.

To summarize the findings on coordination, the assumption is made that the temporal constraints are pushing the movement pattern towards some kind of optimal movement pattern that has on the one hand fewer DOF to handle, while on the other hand still meets the restricted properties of the catching arm. Bernstein (1967) recognized the redundancy of DOF in many tasks. How these DOF are mastered and organized into an appropriate action is affected by the constraints in action during task execution (Newell, 1986; Ko et al., 2003). While Bernstein's theory has been elaborated in the context of motor learning and development (Vereijken et al., 1992; Mitra, Amazeen, & Turvey, 1998; Newell & Vaillancourt, 2001), no clear predictions as to which changes in DOF are to be expected when a movement must be executed within severe temporal constraints are available so far. In this study, we showed that temporal constraints lead to a considerable reorganization of the coordination pattern of the catch. The stronger coupling between hand and elbow indicates that more DOF are simultaneously involved in the movement (see Vereijken et al., 1992). Hand and elbow appear to be organized into a coordinative structure that is able to meet the temporal constraints of the catch. This reorganization is not an all-or-nothing process, but a gradual shift from independent control of each joint towards a pattern in which several joints act as a single unit. In addition, the relative freezing of the shoulder joint with increasing temporal constraints contributes to an even greater reduction of the number of DOF involved in the movement control.

Next to the change in organization, gradual changes in the consistency of the patterns observed occurred as well. In general, the extent of joint coupling tended to be proportional to the intra-subject variability of the movement: as joints moved in closer relation to each other, the movements were produced more consistently (see also Temprado et al., 1997). On the one hand, an increase in movement consistency (i.e., a lower intra-subject variability) with increasing temporal constraints was clearly present in the cross-correlations between elbow—the joint responsible for most of the transport of the hand—and the hand—responsible for the manipulation. On the other hand, the disconnection of shoulder and hand angles was accompanied by an increased intra-subject variability, which indicates a less consistent movement pattern with increased temporal constraints. The important decrease in intra-subject variability in elbow-hand coordination also argues for the emergence of a coordinative structure that is most functional under severe temporal constraints. In this way, not only are the task demands met by a significant reorganization of the DOF involved, but the coordinative structure also becomes more and more consistent with increasing temporal demands. It is obvious that a consistent coordination pattern is an advantage when very little time is available for corrective movements.

To conclude, a decrease in catching performance was present as temporal constraints increased. Despite this decline in performance, both quantitative and qualitative adaptations were implemented to deal with the imposed temporal constraints. On the one hand, the catcher gains extra time by intercepting the ball more backward and moving the hand along a straighter trajectory to this interception point. By adapting a wider hand aperture before initiating the grasp, extra space is bought as well. On the other hand, important changes in the coordination pattern were identified with increasing temporal constraints, namely a gradual shift from relatively independent control of separate joints to a coordination pattern in which several joints act as one unit. Notwithstanding the fact that the perceptuo-motor system is subject to physical restrictions, a combination of emerging coordinative structures and fixation of segments allowed the catcher to keep the number of degrees of freedom to a manageable portion.

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