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published in
Experimental Brain Research
2010

DOI (link to publisher)
10.1007/s00221-009-2102-0

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Tijtgat, P. T. L., Bennett, S. J., Savelsbergh, G. J. P., de Clercq, D., & Lenoir, M. (2010). Advance knowledge effects on kinematics of one-handed catching. *Experimental Brain Research*, *201*(4), 875-884.
https://doi.org/10.1007/s00221-009-2102-0

Exp Brain Res (2010) 201:875–884
DOI 10.1007/s00221-009-2102-0

RESEARCH ARTICLE

Advance knowledge effects on kinematics of one-handed catching

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Received: 13 July 2009 / Accepted: 13 November 2009 / Published online: 1 December 2009

Abstract The purpose of this experiment was to examine the effects of advance knowledge on the kinematics of one-handed catching. Balls were launched from a distance of 8.4 m by a ball-projection machine with adjustable launching speed. Fifteen skilled ball catchers caught 160 balls with their preferred hand under blocked-order (4 blocks, each comprising 20 trials at 1 of 4 different ball speeds) or random-order (4 blocks, each comprising 20 trials of 4 different ball speeds) conditions. By projecting balls with different ball speeds from a fixed position, it was possible to modify the temporal constraints of the catching task. In both the blocked-order and random-order conditions, catching performance (number of catches, touches and misses) decreased with increasing temporal constraints. Analysis of successful trials indicated that this equal level of catching performance was achieved with different movement kinematics. Specifically, there was a change in movement time, latency, wrist velocity profile, and coefficient of straightness. Based on expectancy of previous trials, movement kinematics was scaled to ball speed in the blocked-order condition whereas in the random-order condition, participants exhibited a more default initial response. However, this latter mode of control was functional in that it increased the likelihood of success for the higher ball speeds while also providing participants with a larger temporal window to negotiate the unexpected temporal constraint on-line for the lowest ball speed.

Keywords Ball catching · Advance knowledge · Blocked- versus random-order · Kinematics · Planning-control

Introduction

It is well documented that the human system is capable of taking advantage of advance knowledge when performing motor tasks (Zago et al. 2009), and that this may emanate from different forms and/or on different time scales. For instance, on a short time scale, it has been shown that precueing with advance knowledge on direction and extent of motion (Rosenbaum 1980) or target location and impending visual condition (Hansen et al. 2006) can facilitate rapid aiming tasks, whereas on a longer time scale (i.e., when more time passes between receiving advance knowledge and movement execution), advance expectations can be formed based on the history of previous pitches in baseball hitting (Gray 2002a, b). In the latter case, advance information regarding previous stimuli can be incorporated into an internal model of the ball approach trajectory that facilitates

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successful performance of an interception task (Zago et al. 2004; Senot et al. 2005; Lopez-Moliner et al. 2007). Recent work has suggested that advance information processing during action preparation in a catching task has been located in the left parietal posterior cortex (Nader et al. 2008).

Advance knowledge is also implicitly available when the task is completed in a predictable order, and can lead to different interceptive behavior as compared to an unpredictable order. In a study by Daum et al. (2007), which required targets moving in a desktop virtual environment to be intercepted with a haptic interface, it was found that a context of unpredictable target motion resulted in a higher maximal interception speed. It was suggested that when advance knowledge of target direction was absent (unpredictable), participants used a "more risky and less accurate strategy" (Daum et al. 2007, p. 489) that involved attempting to match the interception object to the moving target as quickly as possible in order to minimize the subsequent distance to the target after a possible change of direction. Importantly, this type of motor control indicates that at least part of the response is prepared in advance of movement onset and hence is in contrast to the suggested exclusive reliance on continuous control during interceptive actions (Bootsma et al. 1997; Montagne et al. 1999; Dessing et al. 2002).

One of the main advantages exhibited when provided with advance knowledge in aiming studies is that it enables participants to modify temporal aspects of motor action. First, when advance knowledge is provided regarding the number of items to be processed (i.e., which targets from a larger set should be responded to), there is a reduction in reaction time (Khan et al. 2008). Second, by providing advance knowledge on target location, it is possible to rely more on pre-planning of movement kinematics, which is then reflected in less need for on-line control and a reduction in movement time (Borysiuk and Sadowski 2007). However, it is important to note that a distinction has to be made between self-paced motor tasks, in which participants are typically instructed to act as quickly and accurately as they deem possible (Elliott and Allard 1985; Khan et al. 1998, 2002), and externally paced tasks such as interceptive actions, which require a specific spatiotemporal relationship between the approach object and responding effector to be established and maintained. As a consequence of these different timing constraints (i.e., internally vs. externally imposed), aiming for stationary objects is prone to a speed-accuracy trade-off, whereby there is a shift in the amount that movement kinematics are planned in advance or adjusted on-line. It remains to be determined, however, if the same mode of control operates in a catching task, which has externally imposed temporal constraints. Recently, it has been shown in two-dimensional interceptive hitting tasks that movement time and peak transport velocity can be varied independently in order to meet the space–time accuracy demands imposed by different target speeds and sizes (Tresilian et al. 2009). For example, participants can achieve better temporal accuracy by maintaining a higher peak wrist velocity, even if there is an increase in overall movement time. In current study, it will be investigated if the same independent control strategy is present in a three-dimensional catching task.

To date, studies on catching under different temporal constraints have shown that humans are capable of adapting their movement kinematics to increasing ball speeds, although a decrease in catching performance cannot be entirely overcome (Laurent et al. 1994; Mazyn et al. 2006). However, while these studies used ball speeds up to 19.7 m/s (Mazyn et al. 2006) in order to challenge human catching abilities with extreme temporal constraints, it is relevant to remark that the different ball speeds were received in a blocked-order. This methodological constraint may have facilitated a mode of control by which advance knowledge of ball speed from the preceding balls was incorporated and influenced the subsequent response. Therefore, it is not clear whether the decline in latency time (LT) that occurred with increasing temporal constraints was solely a consequence of the temporal constraint itself, or whether an "extra 'squirt' of intentional information" (Button et al. 2000, p. 28), which in this case would be based on advance knowledge of the expected ball speed, had an effect on the information processing. Likewise, one could ask if the observed relationship between an expected temporal constraint and kinematic measures such as movement time (Laurent et al. 1994; Mazyn et al. 2006), velocity profile of the wrist (Laurent et al. 1994) or rectilinearity of the wrist trajectory (Laurent et al. 1994; Mazyn et al. 2006) was not also biased by advance knowledge of ball speed. In this respect, it is relevant to note that in a ball catching experiment with mechanical perturbations of the wrist, Button et al. (2002) found that when advance knowledge of such a perturbation was announced, the wrist velocity had a higher peak and occurred earlier during the unfolding of the catch.

Therefore, the purpose of the current experiment was to examine the effects of advance knowledge on the kinematics of one-handed catching, which unlike internally paced aiming movements, is subject to externally imposed temporal constraints that must be met while also satisfying severe spatial constraints (i.e., high accuracy and precision of hand placement relative to the ball trajectory). To this end, a blocked-order versus random-order design was implemented in order to create distinct conditions of certainty and uncertainty regarding impending ball speed and hence temporal constraints. Based on previous studies of movement kinematics in interception tasks, it was hypothesized that under blocked-order conditions a close coupling between ball speed and spatiotemporal adaptations would be evident. An earlier movement onset under higher temporal constraints was expected to be accompanied with a transport velocity that was adjusted to the specific temporal constraint (Laurent et al. 1994; Li and Laurent 1995; Mazyn et al. 2006). However, a different transport velocity profile was expected under random-order conditions, with a higher and earlier occurring maximal wrist velocity (Button et al. 2002; Daum et al. 2007), independently of the unexpected temporal constraint.

Methods

Participants

In order that participants could be successful under the rather demanding temporal constraints imposed in the experiment, and hence to ensure that there was no floor effect, it was required that they had partaken in some form of ball sport (i.e., soccer, tennis, volleyball) for several years, and that in a pre-test they could catch 14 out of 20 balls at a ball speed of 13.3 m/s. In addition, to ensure that catching performance was not influenced by limitations in standard functioning of the visual system (see Mazyn et al. 2004), participants were required to achieve visual acuity of 0.90 on the Snellen E-chart, as well as normal stereo acuity of 40 s of arc on the Random Dot Stereo Butterfly test battery (Stereo Optical Company, Inc., Chicago, USA). Having scanned volunteer participants on these criteria, 15 male self-declared right handed participants (mean age: 21.5 ± 2.6 years) were selected. All participants gave their written informed consent in the experiment, which was approved by the Ethical Committee of the host University.

Task and apparatus

Participants were asked to stand still in a relaxed standing position with their feet parallel, arms besides the body with the thumb of the right hand holding a switch located on the right thigh, and head upright with gaze located straight ahead. Yellow, mid-pressured tennis balls were launched at a distance of 8.4 m from the participant's frontal plane by a ball-projection machine (Promatch/Mubo B.V., Gorinchem, The Netherlands) at four different speeds (9.4 ± 0.08, 11.4 ± 0.36, 13.3 ± 0.23, and 15.8 ± 0.16 m/s), resulting in ball flight times of 896 ± 7.5, 737 ± 24.3, 629 ± 11.0, and 532 ± 5.5 ms respectively.[1] Small inter-trial variability for each ball speed was inevitable and was reflected by a coefficient of variation between 0.9 and 3.2%. A higher ball speed resulted in a lower ball flight time and a higher temporal constraint. The initial height of the ball machine and launch angle was adjusted so that the balls arrived above the participant's right shoulder for each of the four approach speeds with a spatial standard deviation of not more than 11 cm. In order to avoid visual anticipation of launching angle, and hence the ball approach speed, the ball machine was covered with black plastic that had a small cut-out section through which the balls were released; an opto-electric device was mounted at the exit of the ball machine to detect the time of ball release. Finally, to minimize auditory anticipation of the moment of ball release, as well as ball speed, participants wore headphones that minimized sound generated by the ball machine during ball release. A face shield was worn to protect the face, while not disturbing access to the full visual field.

The catching movement with the right arm was tracked with a 3D motion analysis system (Qualisys AB, Gothenburg, Sweden) operating at 240 Hz. Eight infrared cameras were used to register the position of reflective markers that were attached with adhesive tape on key locations of the participant's arm and hand. Specifically, the markers were placed on: shoulder (sulcus intertubercularis of the humerus), elbow (epicondylus lateralis and medialis of the humerus), wrist (processus styloideus of radius and ulna) and hand (Caput metacarpale I, II and V and phalanx distalis of pollux, index and digitus minimus). A switch was attached to the participant's right thigh in order to provide information about the initiation of the catching movement. When the switch was released, an analogue signal (3.9 volts) was generated that was input to the motion analysis system. A microphone was mounted on the forearm near the participant's wrist, and was used to record an audio signal that enabled the moment of ball-hand contact to be derived. An additional webcam was used as a witness camera during every trial.

Procedure

Participants attempted to catch a total of 160 balls that were projected at four different ball speeds in two conditions that differed according to presentation order. In a blocked-order condition, balls were projected in 4 blocks of 20 trials in which the same ball speed was repeated from trial-to-trial. The order of the blocks was randomly assigned across participants. In a random-order condition, 80 trials were randomly ordered and delivered in 4 blocks such that each ball speed was received 20 times. By using a fully randomized order, it was possible that the same ball speed could be repeated from trial-to-trial. Eight participants started in the blocked-order condition, seven in the random-order condition.

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[1] Ball flight times, resultant ball speeds and landing locations were evaluated in a pilot study conducted prior to the experiment. High Speed Cameras (Bassler AG, Ahrensburg, Germany) registered at 100 Hz the moment the ball left the ball machine and contacted a panel that was at 8.4 m from the ball machine (participant's frontal plane).

Every trial followed the same procedure. Before the ball was launched, the participant looked at the experimenter. After a signal from the experimenter (i.e., raising of the right-hand thumb), the participant focussed his gaze on the ball machine and was aware that a ball would soon be released. Participants were instructed to catch as many balls as possible but they were given no further explanations on the purpose of the experiment in order to avoid conceivable anticipation due to this prior knowledge (e.g., the supposition that trials would arrive at the same ball speed in the blocked-order condition). Trials in which the participant or experimenter reported that there was a major deviation of the normal flight path were not examined. These trials were retaken after each block of 20 trials in the blocked-order condition and after the 80 trials in the random-order condition.

Dependent measures and data analysis

Each trial was scored as a catch, a touch (ball-hand contact, but no catch) or a miss (no ball-hand contact) (see Bennett et al. 1999). Successful trials were further examined by means of a kinematic analysis completed using proprietary motion analysis software (Visual 3D v4.00.17, C-motion Inc., Gaithersburg, MD, USA). Several kinematic variables were derived from the time-synchronized analogue signals of the optoelectronic trigger, thigh-located switch and microphone, in combination with the 3D-coordinates of the markers positioned on the catching arm and hand. The position data from the markers was filtered with a Butterworth low-pass filter of second recursive order at a cut-off frequency of 10 Hz. Due to a technical problem, data from one of the participants could not be included in the kinematical analysis.

Following on from the work of Mazyn et al. (2006), the following kinematic measures were extracted: response time (RsT), which is the total duration from the moment the ball first appeared until the moment of ball-hand contact; latency time (LT), which is the time between ball appearance and release of the thigh-located switch; movement time (MT), which is the time between release of the thigh-located switch and ball-hand contact; grasping time (GT), which is the time between maximal hand aperture and ball-hand contact. From the momentary wrist velocity, that was calculated as the resultant of the velocities in the x, y and z axes, the following variables were determined: initial wrist velocity (WrVelini), which is the mean wrist velocity during the first 100 ms after release of the thigh-located switch; peak wrist velocity (PeakWrVel) during the catching action; time to peak wrist velocity (TtoPeakWrVel), which is the time between movement onset and the moment of peak wrist velocity; and time after peak wrist velocity (TafterPeakWrVel), which is the time between peak wrist velocity and ball-hand contact. The coefficient of straightness (CoS) was also extracted and specifies the rectilinearity of the wrist path. CoS is the total distance the wrist covers between movement onset and ball-hand contact divided by the shortest path possible between these two points multiplied by 100 (see also Mazyn et al. 2004, 2006, 2007). We also calculated DxW, which is the linear distance between the position of the wrist at movement onset and ball-hand contact in the anterior-posterior axis (x axis). Peak of hand aperture (PeakHA) was determined as the maximal linear distance between thumb and index during the unfolding of the catch.

The number of catches, touches and misses were submitted to separate 4 ball speed (9.4, 11.4, 13.3, 15.8 m/s) × 2 condition (blocked-order, random-order) ANOVA with repeated measures on both factors. Intra-participant mean data from the successful trials for each kinematic measure were calculated and submitted to separate 4 ball speed (9.4, 11.4, 13.3, 15.8 m/s) × 2 condition (blocked-order, random-order) ANOVA with repeated measures on both factors. Finally, in order to elucidate the differences between caught and touched trials, additional ANOVA with repeated measures were executed on the intra-participant mean and standard deviations of the kinematics, with levels depending on the sufficient number of catches and touches for every condition and ball speed. The level of significance was set at $p \leq 0.05$. In the case of violations of the sphericity assumption, F values were adjusted with the Greenhouse–Geisser procedure. Significant main and interaction effects were further analyzed using Newman–Keul post-hoc tests ($p < 0.05$).

Results

Performance outcome

A main effect of ball speed was evident for number of catches ($F_{2,30} = 81.804$ $p < 0.001$), touches ($F_{3,42} = 81.179$, $p < 0.001$) and misses ($F_{1,20} = 19.158$, $p < 0.001$). There were no significant main effects of condition or interaction effects for number of catches or touches. Post-hoc testing indicated that in both the blocked-order and random-order conditions, there was a significant decrease in the number of balls caught ($p < 0.001$), and a corresponding increase in number of touches as ball speed increased from 11.4 to 13.3 m/s, and then again from 13.3 to 15.8 m/s ($p < 0.001$); the number of catches and touches did not differ between the two slowest balls speeds. Participants caught almost all balls at the lowest ball speed and only half of the balls at the highest ball speed (see Fig. 1). There was, however, a significant ball speed × condition interaction for the amount of balls missed ($F_{1,17} = 9.083$, $p < 0.001$). While there were a very small number of misses overall, there was a difference between the conditions at the highest speed. On average

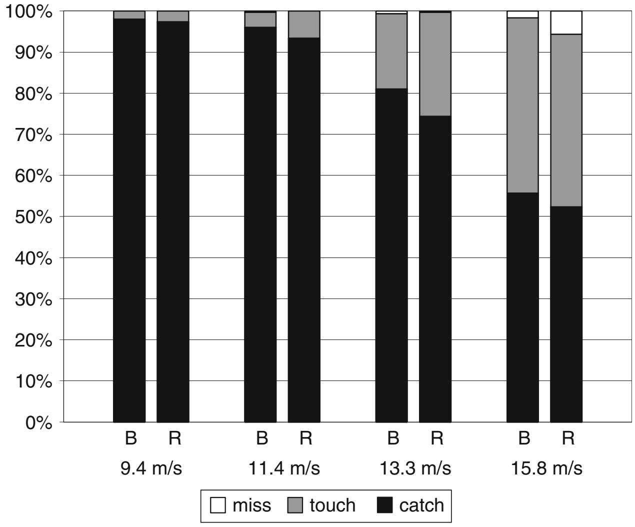

Fig. 1 Catching performance, touches and misses at the four ball speeds for blocked-order condition (*B*) and random-order condition (*R*) as a percentage of total catching trials at that ball speed and for that condition

1.13 balls were missed in the random-order condition compared to 0.33 balls missed in the blocked-order condition ($p < 0.001$).

Kinematics

Table 1 shows the means and standard deviations of the kinematic variables as a function of ball speed and condition, as well the resulting interaction effects. For the purpose of brevity, main effects of ball speed and condition are described in the main body text where appropriate.

There was a main effect of ball speed for RsT ($F_{3,39} = 16{,}101.327$, $p < 0.001$), but no main effect of condition or an interaction effect. Post-hoc testing indicated that RsT decreased for each increase in ball speed ($p < 0.001$). There were, however, significant interaction effects for MT ($F_{3,39} = 6.307$, $p < 0.01$) and LT ($F_{3,39} = 15.198$, $p < 0.001$). MT ($p < 0.001$) and LT ($p < 0.001$) were reduced in both conditions as ball speed increased from 11.4 to 13.3 m/s and then to 15.8 m/s. Importantly, though, at the lowest ball speed, LT was shorter ($p < 0.001$) and MT longer ($p < 0.001$) when catching in the random-order condition than in the blocked-order condition (see Fig. 2).

Figure 3a shows the inter-participant mean wrist velocity profiles at each ball speed and condition. The intra-participant mean wrist velocity profiles of three representative individuals are presented in Fig. 3b–d. It can be seen that, from movement initiation on, the wrist velocity profiles were different between ball speeds in the blocked-order condition (left panel), while they were more similar between ball speeds for the first 100 ms in the random-order condition (right panel). This was reflected in a significant interaction effect for WrVelini ($F_{3,39} = 20.81$, $p < 0.001$). Initial wrist velocity differed with each ball speed in the blocked-order condition whereas in the random-order condition only the initial wrist velocity for the lowest ball speed was different from the other three ball speeds ($p < 0.005$). The interaction effect for PeakWrVel also approached conventional levels of significance ($F_{2,22} = 3.396$, $p = 0.06$). PeakWrVel tended to increase with each increase in ball speed for both conditions ($F_{3,39} = 176.807$, $p < 0.001$) but this amplitude scaling was more evident when trials were received in blocked-order. A significant ball speed × condition interaction was noted for TtoPeakWrVel ($F_{2,21} = 14.740$, $p < 0.001$) and TafterPeakWrVel ($F_{3,39} = 33.126$, $p < 0.001$). Post-hoc testing indicated that TtoPeakWrVel did not change over ball speed for the random-order condition, whereas in the blocked-order condition there was a difference between the two lowest ball speeds ($p < 0.001$) as well as between the two highest ball speeds ($p < 0.001$; Fig. 2 and 3), showing evidence of time scaling. TafterPeakWrVel was reduced for both conditions with increasing ball speed ($p < 0.001$), but was longer in the random-order condition than the blocked-order condition at the two lowest ball speeds ($p < 0.001$) and shorter at the highest ball peed ($p < 0.001$).

There was a significant interaction effect for coefficient of straightness ($F_{3,39} = 8.681$, $p < 0.001$). Post-hoc tests revealed that for both conditions the two higher ball speeds (13.3 and 15.8 m/s) resulted in a more rectilinear trajectory as the wrist was moved to the place of contact ($p < 0.001$). There was, however, a difference between conditions at the lowest ball speed, with a higher CoS exhibited in the random-order condition than the blocked-order condition ($p < 0.001$). The effect of ball speed approached significance for DxW ($F_{2,20} = 3.590$, $p = 0.06$) and tended to be lower at the highest speed as compared to the lower ball speeds. For PeakHA there was a main effect of ball speed ($F_{3,39} = 27.04$, $p < 0.001$) and condition ($F_{1,13} = 4.477$, $p = 0.05$). PeakHA increased as a function of each increase in ball speed and was on average 0.2 cm greater for the blocked-order condition as compared to the random-order condition. There were no significant effects of ball speed or condition for grasping time (GT). Grasp initiation occurred at a constant time of approximately 60 ms before ball-hand contact.

For the highest ball speed, 2 outcome (catch, touch) × 2 condition (blocked-order, random-order) ANOVA with repeated measures on both factors were calculated on the intra-participant mean and standard deviations of the kinematics, since for that ball speed there was a sufficient amount of catches and touches for each participant. No significant effects were found for RsT, but the intra-participant standard deviation of RsT was larger (±2 ms) for touches than for catches in both conditions ($F_{1,13} = 5.263$, $p < 0.05$). However, including touches in the analysis resulted in a

Table 1 Means and standard deviations (SD) of kinematical variables for the four ball speeds under the blocked- and random-order condition. Statistical interaction effects of ball speed × condition for every dependent variable

	Blocked-order				Random-order				Ball speed × condition		
	9.4 m/s	11.4 m/s	13.3 m/s	15.8 m/s	9.4 m/s	11.4 m/s	13.3 m/s	15.8 m/s	*F* value (*df*)	*p*	η_p^2
RsT (ms)											
Mean	870.6	684.4	572.4	500.1	866.7	685.7	574.8	501.4	2.109 (3)	0.11	0.140
SD	9.9	12.5	6.5	6.7	11.8	11.0	7.8	8.2			
MT (ms)											
Mean	597.5	450.7	358.1	297.7	617.7	458.7	358.2	293.3	6.307 (3)	0.001*	0.327
SD	46.4	27.8	17.0	16.4	40.3	24.1	18.2	20.3			
LT (ms)											
Mean	273.2	233.4	213.5	201.8	248.5	227.2	216.3	207.5	15.198 (3)	0.000**	0.539
SD	43.0	21.7	14.1	14.8	40.3	23.9	22.0	21.1			
GT (ms)											
Mean	68.9	60.6	63.4	59.8	60.7	61.2	64.4	51.8	0.946 (1.7)	0.43	0.068
SD	40.2	12.4	26.3	20.9	13.4	17.4	27.5	18.5			
WrVelini (m/s)											
Mean	1.2	1.6	1.8	2.3	1.5	1.7	1.9	1.9	20.807 (1.3)	0.000**	0.615
SD	0.2	0.2	0.3	0.4	0.3	0.3	0.3	0.3			
PeakWrVel (m/s)											
Mean	3.16	3.82	4.18	4.87	3.53	4.07	4.36	4.84	3.396 (1.7)	0.06	0.207
SD	0.33	0.32	0.33	0.29	0.46	0.43	0.35	0.43			
TtoPeakWrVel (ms)											
Mean	201.3	164.8	151.6	138.9	169.4	160.2	160.6	162.7	14.740 (1.6)	0.000**	0.531
SD	29.8	16.0	14.0	13.6	25.7	21.3	32.2	23.5			
TafterPeakWrVel (ms)											
Mean	395.3	286.5	206.1	160.3	443.4	303.0	206.7	135.2	33.126 (3)	0.000**	0.718
SD	61.2	36.4	19.8	17.9	65.4	30.3	21.1	19.9			
PeakHa (cm)											
Mean	11.31	11.63	11.91	12.38	11.19	11.50	11.72	11.94	1.284 (3)	0.29	0.090
SD	0.90	0.75	0.93	0.92	0.81	0.85	0.94	0.79			
CoS (%)											
Mean	111.1	108.5	106.8	106.5	112.7	108.8	106.8	106.3	8.681 (3)	0.000**	0.400
SD	2.6	2.5	2.3	2.0	3.3	2.2	1.9	1.8			
DxW (cm)											
Mean	31.3	31.7	31.5	29.2	28.5	30.3	30.6	27.2	0.777 (1.9)	0.51	0.056
SD	10.4	8.0	8.2	8.7	8.6	9.7	9.1	9.5			

* $p < 0.01$; ** $p < 0.001$

significant effect of condition for LT ($F_{1,13} = 6.483$, $p < 0.05$) MT ($F_{1,13} = 5.283$, $p < 0.05$) and WrVelini ($F_{1,13} = 13.215$, $p < 0.005$). LT was on average 9 ms longer and MT 7 ms shorter for random-order catching than for blocked-order catching, while initial wrist velocity was ±0.33 m/s lower. LT approached significance for the outcome × condition interaction ($F_{1,13} = 3.688$, $p = 0.08$): in the blocked-order condition, LT was on average between 201 and 202 ms for both catches and touches, whereas movement started on average later (215 ms) when the ball was touched than when caught successfully (207.5 ms) in the random-order condition. There was a significant interaction for the intra-participant variability of TtoPeakWrVel ($F_{1,13} = 4.718$, $p < 0.05$): whereas the standard deviation of TtoPeakWrVel was the same for the random-order condition whether the ball was caught or touched (±28 ms), variability was greater for touches (78 ms) than for catches (18 ms) in the blocked-order condition. No other significant effects were visible for the kinematic variables and their standard deviations.

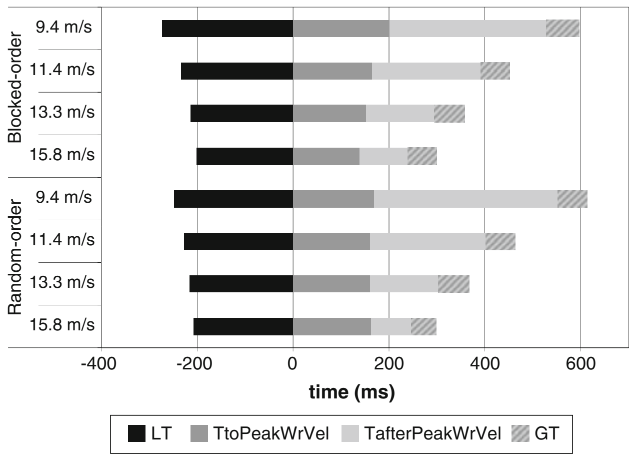

Fig. 2 Overview of the temporal structure of the catching movement at the four ball speeds for blocked-order condition and random-order condition. Zero-point is set at the moment of movement onset. LT is in black, grey shades reflect MT. TafterPeakWrVel includes GT

Discussion

The objective of this study was to explore the effect of advance knowledge regarding temporal constraints of a one-handed catching task on performance outcome and movement kinematics. By presenting balls to be caught at one of four different ball speeds in either blocked-order or random-order, we aimed to determine if participants' certainty of expectation regarding the temporal constraints of ball trajectory facilitated a modification to the motor response and helped to maintain successful performance. The blocked-order condition was expected to provide knowledge gathered during previous trials regarding the upcoming ball speed, hence resulting in efficient adaptations to the temporal constraints such as an earlier movement onset and a higher maximal wrist velocity under higher temporal constraints. Under conditions of uncertainty about the temporal constraints (random-order ball speed), it was expected that the participants would attempt to minimize errors and hence exhibit a generalized response in which they move their hand with a high and early occurring peak wrist velocity. In this respect, movement kinematics in the random-order condition would be largely independent of the specific temporal constraint of each trial.

Consistent with previous work (Laurent et al. 1994; Bennett et al. 1999; Mazyn et al. 2006), it was found that catching performance decreased with increasing ball speed and hence increasing temporal constraints. The decrease in number of catches was accompanied by an increase in number of touches (see Fig. 1), indicating that the fine spatio-temporal control of the catching action required to successfully grasp the ball, was affected (Bennett et al. 1999). Although only 1% of the balls were totally missed, there was a larger number of misses when attempting to catch balls projected with the highest speed in the random-order condition compared to the blocked-order condition. This finding might indicate a very marginal advantage in terms of outcome performance in blocked-order conditions due to an advance knowledge effect but overall there was little difference between blocked-order and random-order catching performance.

Analysis of successful catches indicated that there was a change in kinematics as a function of temporal constraints (see Table 1 and Fig. 2, see also Laurent et al. 1994; Mazyn et al. 2006). In both the blocked-order and random-order conditions, the increase in ball speed resulted in a reduced response time, latency time, movement time, higher peak wrist velocity, a more rectilinear movement trajectory and a higher peak of hand aperture. The observed adaptations in MT and PeakWrVel confirm catchers' ability to meet the time-accuracy demands of the task at hand (Tresilian et al. 2009). Perhaps surprisingly, DxW was only marginally ($p = 0.06$) different between ball speed-conditions. The backward shift of the place of ball-hand contact under increasing temporal constraints that has previously been reported (Laurent et al. 1994; Mazyn et al. 2006) was much smaller in the current study and only evident at the highest ball speed-condition. This unexpected result, greater differences could be expected especially in the blocked-order condition, might be explained by small methodological differences between these studies. For example, visual anticipation before ball release could not be avoided in the study of Mazyn et al. (2006). This could account for the greater LT and smaller MT in the current experiment, because participants might have waited longer in order to acquire more visual information, followed by a reduced movement execution.

Despite not permitting outcome performance to be maintained (see above), the adaptations to the spatio-temporal control of the catching hand were functional and resulted in the grasp being initiated at a constant time of 60 ms before ball-hand contact (Fig. 2). Similar findings of a constant time-to-contact strategy for the timing of the grasp in catching have been reported in many other studies (Lacquaniti and Maioli 1989; Savelsbergh et al. 1991, 1993; Laurent et al. 1994; Button et al. 2002; Mazyn et al. 2006).

However, there was also a general tendency for advance knowledge of ball speed to influence movement kinematics at the lower balls speeds. The catching movement was initiated earlier after ball release (i.e., reduced LT) in the random-order condition and was accompanied by a greater magnitude of peak wrist velocity that occurred at a similarly earlier time of 160–170 ms after movement onset; for evidence of a comparable adaptation in wrist velocity in the face of an unexpected perturbation, see Button et al. (2000, 2002). As shown in Fig. 3, the

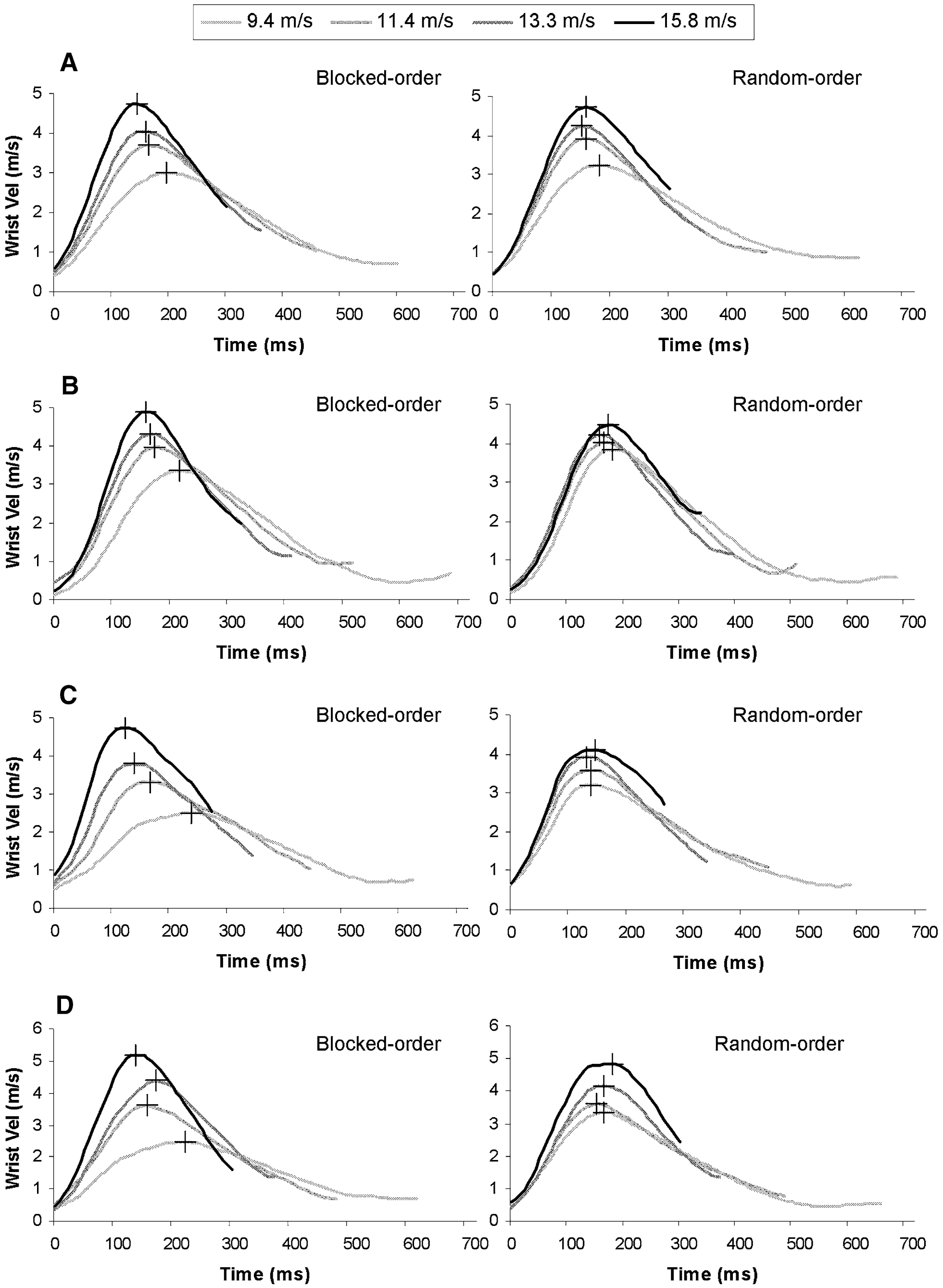

Fig. 3 Wrist velocity profiles for blocked-order (*left panel*) and random-order (*right panel*) conditions at the four ball speeds. Mean wrist velocities of all participants are represented (**a**) as well as three individual participants AP (**b**), JB (**c**) and RB (**d**). *Plus symbol* represent Peak Wrist Velocity

initial wrist velocity (first 100 ms) was clearly adjusted to ball speed in the blocked-order condition (left panel), whereas some overlap in the initial part of the wrist velocity was visible in the random-order condition (right panel, see also van Donkelaar et al. 1992). The magnitude of peak wrist velocity was scaled to ball speed in both conditions, although to a lesser extent for the random-order condition. Nevertheless, whereas the timing of peak wrist velocity in the blocked-order condition co-varied with ball speed (Fig. 3, left panel), no such time scaling of wrist velocity was evident in the random-order condition (Fig. 3, right panel). These differences in wrist velocity profile were more evident for some participants (Fig. 3b, c) than for others (Fig. 3d). Having initiated the movement earlier and with a greater magnitude of initial wrist velocity, participants then moved with a less rectilinear hand path in the random-order condition than the blocked-order condition at the lowest ball speed. In combination, these adaptations resulted in a longer movement time, which is consistent with a mode of control in which participants use a larger temporal window to negotiate the unexpected temporal constraint on-line. Importantly, however, it was only possible to use this mode of control when the temporal constraints were not too severe.

In an attempt to elucidate the possible reasons for failures, kinematics of caught trials were compared to touched trials. This was only possible at the highest ball speed, since for that ball speed-condition sufficient trials were evident to justify an analysis. Response time was more variable within participants for trials that were touched as compared to catches, indicating a more stable timing in successful trials, even though the differences were very small (±2 ms). Inclusion of the touched trials with the caught trials resulted in a significantly longer LT and shorter MT for random-order catching as compared to blocked-order catching. At this highest ball speed, initial wrist velocity was higher for blocked-order catching than for random-order catching. It seems that advanced knowledge of ball speed resulted in a higher initial wrist velocity because a high ball speed was expected. There was also a near significant interaction for LT: in random-order trials that were touched, movement onset was delayed as compared to blocked-order and successful random-order catching. The absence of advance information of ball speed might have resulted in an unbalanced timing with too much time for movement preparation and too little for movement execution. For blocked-order catching, failures were characterized by a greater variability to reach the peak of wrist velocity. However, while explanations for failure at that ball speed might be speculative, catching performance remained equal for both conditions.

Although advance knowledge of ball speed did not result in a significant greater amount of balls caught in this experiment, it can be argued that participants use of different movement planning and control strategies were best fit under the given circumstances. In the blocked-order condition, the advance knowledge of ball speed permitted a movement strategy closely adapted on a trial-by-trial basis to the temporal constraints. For instance, when participants knew that a slow ball was coming, they delayed movement onset and then adapted the subsequent movement to the remaining time of flight. In the random-order condition, however, it would seem that participants produced an initial response that had more default time and velocity characteristics. Such an approach has been reported previously in several other tasks and is suggested to be adaptive in the sense that it gives participants increased opportunity to respond to an uncertain situation. Indeed, there would have been clear benefit to respond with an early movement of high magnitude velocity in the random-order condition because balls projected at the highest speeds would have been very difficult to catch had participants adopted similar movement kinematics to those used for the slower ball speeds in the blocked-order condition. The cost associated with using a initial default response would in fact be quite low because participants could continue with this response if the ball speed was high, while they could modify their movement kinematics online if the ball speed actually turned out to be lower than initially planned for. In contrast to the blocked-order condition, where adaptations to ball speed could be prepared well in advance, it was only at the very moment of ball release (i.e., when the first visual information was available) that participants in the random-order condition could start to incorporate adaptations to the specific ball speed in their movement plan and subsequent control. Before that moment of ball release, the uncertainty of ball speed could only lead to a default preparation, which resulted in the observed more default motor answer. Note that this different movement strategy still resulted in an equally efficient catching performance that provides additional evidence of the capability of the perceptuo-motor system to adapt its actions depending on the imposed task constraints (van der Kamp et al. 1997; Mazyn et al. 2007).

Clearly, then, the findings in the current study of differences between catching under blocked-order and random-order temporal constraints suggest that participants exerted some cognitive control over their movement execution. This interpretation is difficult to reconcile with an exclusive on-line control strategy in which the influence of cognitive operations such as expectation and prior knowledge is rejected (Michaels 2000; Michaels et al. 2001). However, we do not interpret these findings to suggest that the human system is not able to control most of the daily live activities by means of direct feedback loops based on on-line visual information. Instead, we agree with the suggestion that some kind of internal representation might aid at least a part of movement control (Norman 2002; Zago et al. 2009; Nitsch 2009) and that this is even more pronounced in so-called unnatural (Jensen et al. 1989) sport situations that impose severe temporal constraints (Regan 1997).

For future research that is intended to be relevant for real life situations in which there is trial-to-trial variability in ball speed due to human factors (Ranganathan and Carlton 2007; Werner et al. 2008; Moras et al. 2008), the results of the current study highlight the importance of randomizing ball speeds. Advance knowledge based on preceding trials has a strong influence on the control of catching movement that is not evident in outcome performance. While it remains unclear what contribution to the observed differences in movement kinematics is made by recent experience of previous trials and/or the expression of explicit knowledge of upcoming trials (de Lussanet et al. 2002; Song and Nakayama 2007), it will be interesting to examine in future work the influence of spatial uncertainty on interceptive behavior, in order to examine human behavior in representative designs (Araujo et al. 2007). Only then it will be possible to generalize empirical findings to a real life situation.

In conclusion, the current experiment shows that advance knowledge of ball speed had an influence on movement kinematics, although catching performance remained the same. Trials that were presented in blocks of the same ball speed led to a better scaling of movement kinematics based on expectancy from previous trials.

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