Planning and on-line control of catching as a function of perceptual-motor constraints

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Abstract

Two experiments were conducted in order to investigate the adaptability and associated strategies of the human perceptuo-motor system to deal with changing constraints. In a catching task, perceptual-motor constraints were internally controlled by coupling movement onset of the catch and the illumination circuit in the lab: upon the first movement of the catcher, all lights went out within 3 ms. The authors studied (a) how much movement time catchers prefer if no visual information is available after movement onset, and (b) how movement execution changes under such temporal constraints. It was hypothesised that, in order to accomplish successful catching behaviour, (1) movement initiation would be postponed in order to allow sufficient information uptake before the lights went out, and (2) an alternative control strategy would have to be mobilised, since on-line control becomes inappropriate when catching in the dark. In the first experiment, the adaptation process to the light–dark paradigm was investigated. In the second experiment, the conclusions from experiment 1 were challenged under varying ball speeds. In order to maintain catching performance, subjects initiated the catch approximately 280 ms before ball-hand contact. Next to changes in temporal structure of the catch and subtle kinematic adaptations, evidence for a change in the control mode emerged: while an on-line control strategy was adopted under normal illumination, catching movements seemed to be executed as planned in advance when catching in the dark. Additionally, perceptual constraints seem to determine the time of movement initiation, rather than motor

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constraints. These results emphasize the capability of the human perceptuo-motor system to adjust promptly to new task constraints.

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1. Introduction

The visual sensory system is a key factor for accomplishing everyday skills as well as for achieving sports skills such as the goalkeeper blocking the ball or the fencer parrying an opponent’s attack. The relevant information is not only extracted in order to prepare and initiate an appropriate motor response, it is also used to continuously adjust the on-going action. In the latter control mode, the movement gets more and more tuned as the completion of the action approaches. However, since the motor apparatus has its intrinsic limitations as well, both perceptual and motor constraints have to be dealt with in order to accomplish a successful interception.

In recent years, the notion that our movements are continuously adjusted upon the incoming stream of information has been widely accepted (e.g. Caljouw, van der Kamp, & Savelsbergh, 2006; Montagne, 2005; Montagne, Laurent, Duery, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994; Savelsbergh, Whiting, & Bootsma, 1991). Online adaptation to the relevant information is a strategy that allows fast and appropriate correction of the on-going movement. Specifically in interceptive tasks like ball catching or avoidance tasks similar to traffic situations (te Velde, van der Kamp, Barela, & Savelsbergh, 2005), this strategy gained ascendancy over the more predictive theories that have dominated the field previously (see Bootsma, Houbiers, Whiting, & van Wieringen, 1991; Lee & Young, 1985; Regan, 1997; Tresilian, 2005; Tyldesley & Whiting, 1975).

In catching, on-line adaptation has been documented until the last 100 ms or less before the arrival of the ball at a catcher’s hand (e.g. Savelsbergh, Whiting, Pijpers, & van Santvoord, 1993). This temporal interval is usually interpreted as to correspond to the visuo-motor delay, which is the time necessary to integrate a new stream of information into the on-going movement. Although continuous guidance is extensively documented in studies in which the relevant information was continuously present, this does not mean that a catcher does not or can not plan his/her action in advance. Recently, Lenoir and collaborators showed that volleyball players use predictive as well as prospective information of a rotating ball, allowing a successful reception at the accurately assessed landing place of a curving sidespin volleyball serve (Lenoir, Vansteenkiste, Vermeulen, & De Clercq, 2005).

Successful catching thus requires the adequate use of – mainly visual-continuous information for the guidance of the temporal as well as spatial aspects of the action. There is however evidence that continuous visual feedback is not necessary for accurate temporal and spatial control of an interception. Desmurget, Péllisson, Rossetti, and Prablanc (1998) showed that we do not need continuous visual information for the accurate positioning of the hand in an interception task. In addition, when the speed of movement execution is high, the effect of visual feedback on spatial accuracy decreases during reaching (Woodworth, 1899). Brouwer, Brenner, and Smeets (2002) showed that timing of a fast hitting
action did not change when continuous visual information was absent. Whether the effects of visual feedback on timing and positioning found in these studies might be transferred to catching is debatable (Schenk, Mair, & Zihl, 2004). In addition, temporal and spatial aspects in catching appear to be so closely intertwined that a separation between time and position is hard to maintain (Michaels & Oudejans, 1992; Montagne, 2005; Peper et al., 1994; see Brouwer et al. (2002) for a different opinion).

Although continuous visual information is present in most natural catching situations, breaking down the perception-action coupling – for instance by the sudden removal of all visual information – might force an actor to switch from an on-line mode to a planning mode. In visual occlusion studies by Whiting and colleagues, catching performance did not significantly decrease as long as the ball remained visible until approximately the final 280 ms before its arrival at the catcher’s hand (Sharp & Whiting, 1974, 1975; Whiting, Alderson, & Sanderson, 1973; Whiting & Sharp, 1974). Sharp and Whiting (1975) argued that the length of the dark period preceding ball-hand contact is the main limiting factor in successful catching, providing that sufficient visual information of the ball flight is on hand. In the absence of visual information, the final grasping action might be planned in advance during the time preceding the occlusion period, allowing the catcher to successfully continue his catch. Another option would be that the time and place of arrival of the ball might be predicted and held in working memory during the final 280 ms. However, it is unlikely that visual information persists for such an extended time interval (Olivier, Weeks, Lyons, Ricker, & Elliott, 1998).

In the present study, Whiting’s work was replicated, albeit with two major distinctions. First, while the experimenters in the Whiting studies externally imposed the amount of time that the ball was visible, it is worthwhile investigating how much visual information a catcher needs if he is to choose the amount himself. In this study participants triggered the extinction of the lights by the onset of their own catching movement, which entails that no visual information was available once the movement was initiated. This particular set-up implies that participants are confronted with a trade-off between viewing time and movement time. It is hypothesised that when acting like in the normal illumination situation, the dark period before ball-hand contact will be too long. Moreover, when a catcher initiates the action early in flight, he/she must do with (too) little information. The alternative, to postpone the initiation of the catch until enough information is gathered, is more plausible. In the latter case, the increase in the temporal constraints necessitates kinematic changes in the catching movement, analogue to the time and space buying strategies that catchers implement when catching under highly temporal constrained situations (Laurent, Montagne, & Savelsbergh, 1994; Mazyn, Montagne, Savelsbergh, & Lenoir, 2006). For example, the catcher can gain extra time by intercepting the ball more backward and by moving the hand along a straighter trajectory to this interception point. An enlarged maximal hand aperture allowed compensating the decrease in spatial accuracy with increasing speed as well.

A second important methodological aspect that must be mentioned in the traditional occlusion studies is that the hand was already positioned in the “catching zone” when the lights went out. Therefore, the deprivation of visual information primarily influenced the grasping phase of the catch. On the contrary, the gross spatial orientation phase or transport phase was also performed in the dark in the present experiment. This entails that the catcher not only has to deal with the enforced informational constraints, but with increased motor requisites as well to enable a successful performance.
The first aim of this study was to replicate the findings of Whiting et al. (1973) concerning the temporal limits of visual information that is necessary or redundant for a successful catching, and extend them to an intrinsically controlled set-up. According to the findings of Sharp and Whiting (1975), catching would become severely aggravated if a dark period longer than 280 ms precedes ball-hand contact. So if the magnitude of Whiting’s formerly established “Critical Occluded Period” (COP) is correct, and reckoning with the fact that the extra postponement of movement initiation beyond this 280 ms COP would further tackle the limitations of the motor executive, it might be presumed that the participants in the present experiment would opt for delaying movement onset until about 280 ms before the ball reaches the hand. A second objective of the present study was the attempt to identify the control mechanisms that were used during catching under different informational constrained situations. The flexibility of the human perceptuo-motor system might enable the catcher to switch from on-line information integration to a planning/prediction modus, depending on the amount and temporal availability of the visual information. In addition, the self-trIGGERING paradigm allows investigating whether the trade-off is perception driven or motor driven. In the latter case, catchers will postpone their catch until only enough time is left to make a catch at maximal execution speed. A perception driven trade-off would result in the initiation of the catch when the catcher judges that enough information is available.

A first experiment focused on the adaptation process when initially confronted with the light–dark paradigm: the limits of the COP, changes in kinematics of the movement and motor control strategies were ascertained. To examine whether the findings on COP from experiment 1 can be generalized, the light–dark manipulation was extended to varying ball speeds in the second experiment. Such a paradigm also allows further exploration on what constraints are more dominant for triggering movement onset: the perceptual or motor ones.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Physical education students were screened on catching performance using a catching test where tennis balls, launched at a speed of 15.3 m/s, had to be caught with one hand. Students who succeeded at least 17 out of 20 trials were selected to take part in the study. Eventually, a group of 10 men and 10 women ranging in age from 19 to 26 years (mean age 21.5 ± 2.1 years) volunteered for the present experiment that was approved by the Ethics Committee of the Ghent University Hospital. After being informed about the content of the task, all participants gave their written consent. However, in order to prevent interference in the initial part of the experiment, participants were not informed about the unusual illumination condition they were going to be exposed to later on in the experiment. All participants were right-handed catchers and had normal or corrected-to-normal vision.

2.1.2. Task and apparatus

Participants were asked to catch yellow mid-pressure tennis balls with their preferred hand. Balls were projected by a Singly Promatch launching machine (MUBO b.v., Gorinchem, The Netherlands) from a distance of 8.4 m from the participant’s frontal plane at a
speed of 10.5 m/s, resulting in flight times of about 800 ms. An opto-electric device, mounted at the exit of the launching apparatus, was used to detect the time of ball departure (see Fig. 1). A fix launching angle of 25.6° was used in order to keep the flight trajectories of the ball identical from the viewpoint of each participant. Therefore, the launching height of the ball was adjusted to the participant’s body height by lifting the entire launching device. All balls reached the participant in an imaginary circle of 30 cm in diameter with its centre approximately 15 cm above the shoulder of the catching arm. A switch was attached to the lateral side of the participant’s thigh and had to be pressed with the thumb of the catching hand before each trial. The release of this switch provided information about the initiation of the catching movement, and functioned as a light switch in the experimental illumination condition. For safety reasons, participants wore a face shield with clear polycarbonate screen. Earphones were used in addition to block out the noise of the launching device and hence prevent anticipation on the departure of the ball. The flight path of the ball was lit by 50 Luxeon Star Power LED’s mounted in two rows (0.5 m apart) above the ball trajectory. To prevent a strong shading of the underside of the ball, the floor was covered with a broad strip of white paper.

2.1.3. Procedure

The test trials were preceded by five acclimatization catches, which allowed the experimenters to check whether the launching device was adjusted properly to the participant’s height. Two different illumination conditions were presented to the participants. First, 10 catches were performed under normal illumination (full light condition, FL). Next, the participant was faced with the experimental light–dark condition (LD): as long as the switch was pressed, the ball’s trajectory stayed lit. When the catching movement was initiated and hence the switch was released, all lights turned out within 3 ms and the catch had to be accomplished in complete darkness. The participants practiced this light–dark condition in blocks of 10 trials, until a criterion of 7 successful catches out of 10 was achieved. After reaching this criterion for reasonable skilfulness, one more block of 10 trials was undertaken.

At the end of the experiment a functional grasping task was presented to the participant, to explore the speed limits of the motor system. A tennis ball hung down at eye height and at a distance of 75% of the arm length in front of the participant (which entails
a movement that corresponds to the natural arm configuration in unrestricted ball catching). The participant was asked to grasp for the ball as fast as possible with continuous illumination. Five trials were recorded under normal illumination to determine minimum movement time and the maximal velocity by which the arm can be moved towards the ball in a grasping task that requires a similar arm and hand configuration as in the catching task, but without any externally imposed temporal requisites.

2.1.4. Data acquisition
Kinematic data of the 10 catches in the full light condition (FL), the initial 10 trials when faced with the experimental illumination (initial light–dark, ILD) and the final 10 trials after reaching the criterion in the light–dark condition (trained light–dark, TLD) were recorded with a 3D motion capture system (Qualisys, Sweden) at 240 Hz. A composition of eight infra-red camera’s captured the movements of nine reflective markers that were attached with double sided cloth tape onto the participant’s catching arm and hand (processus coracoideus of the scapula, epicondylus lateralis and medialis of the humerus, processus styloideus of radius and ulna, caput metacarpal of digitus medius and external face of the distal phalanx of thumb and index finger). A fix marker was placed behind the participant, 9.5 m from the ball projection machine and served as reference point to determine the exact position of the catcher. The obtained 3D data were subsequently filtered at a cut-off frequency of 10 Hz with a second-order recursive Butterworth filter. Then velocities and angles were calculated from the time series of coordinates, before the dependent variables could be derived.

2.1.5. Dependent measures
To evaluate catching performance, the number of successful catches was considered in each of the light conditions: FL, ILD and TLD. Since the present study focused primarily on the adaptation process of the catching behaviour, successful catches as well as failures were included in the kinematic analysis of the catching movement. Next to catching performance, several kinematic variables that were expected to change due to the perceptual-motor constraints (cfr. temporal constraints: Laurent et al., 1994; Mazyn et al., 2006) were included in the analysis. First, three timing variables that represent the temporal structure of the catch were defined: (1) 

**Latency time** (LT, in ms) as the time that elapsed between the departure of the ball at the launching device and the moment the switch was released; (2) 

**Movement time** (MT, in ms) as the time from initiation of the movement (switch release) to the moment of ball-hand contact (ball-hand contact was determined by the sudden backward acceleration of the metacarpal and finger markers at the time of impact) – a minimum MT to perform the catching movement was derived from the functional grasping task as well – (3) 

**Grasping time** (GT, in ms) as the time that elapsed from the moment the hand opening velocity turns negative after reaching maximal hand aperture, until ball-hand contact. Further kinematic analysis was implemented by considering the following quantitative variables: (4) 

**Peak Hand Aperture** (PeakHa, in mm) as the maximal linear distance obtained between the thumb and index finger during the catching movement; (5) 

**Forward displacement of the wrist** (D×W, in mm) as the linear distance between the position of respectively the wrist at the initiation of the catching movement and ball-hand contact along the sagittal axis; (6) 

**Coefficient of Straightness** (CoS, in %) as the actual traveled path of the wrist divided by the distance of the shortest linear path × 100, specifying
rectilinearity of the wrist trajectory (see also Mazyn, Lenoir, Montagne, & Savelsbergh, 2004, 2006); (7) Peak velocity of the wrist (PVwrist, in mm/s) as the maximal instantaneous velocity of the wrist from movement onset until ball-hand contact, derived from the catching data as well as from the data from the functional grasping task. Finally, within-subject standard deviations of all kinematic variables were considered to evaluate the stability of the acquired movement pattern.

2.1.6. Data analysis

In the course of the experiment a clear distinction in adaptation speed appeared among the participants. Based on the number of practice blocks that was required to reach the postulated criterion, two groups could be discerned: a fast adaptation group (FAG) who attained a satisfying performance level within 1 or 2 blocks of 10 trials, and a slower adaptation group (SAG) that needed more than two practice series to reach the seven-out-of-ten criterion. The mean number of practice blocks that was required in the SAG group was 5.1. This corresponds to an average of 51 trials, compared to 15 trials for the FAG group. Both groups consisted of 10 participants: the FAG counted seven males and three females; the SAG was composed of three males and seven females.

A 3 (light conditions) × 2 (groups) ANOVA analysis with repeated measures on the factor light condition (FL, ILD and TLD) was carried out on all dependent measures. Post hoc comparisons for the retrieved main effects were conducted with an LSD-test, while interaction effects were further analysed by using paired and independent samples T-tests. An alpha level of .05 was used for all statistical tests and the size of the effect was reported by means of the partial Eta squared ($\eta^2_p$). In case of violation of the sphericity assumption in repeated measures ANOVA (epsilon-value < .75; Vincent, 1995), the Huynh-Feldt correction was applied and reported.

2.2. Results

2.2.1. Catching performance

All means and standard deviations of the considered variables are reported in Table 1. A significant main effect of light condition was found on catching performance, $F(2, 36) = 76.893, p < .001, \eta^2_p = .810$. Under both FL and TLD condition, catching performance exceeded performance in the ILD condition: 9.85 and 8.25 successful trials for respectively FL and TLD, compared to 5.15 in the ILD condition. Catching performance was still significantly better under FL compared to TLD. A main effect of group was present as well, $F(1, 18) = 16.095, p < .01, \eta^2_p = .472$; however, this was accompanied by a condition × group interaction effect, $F(2, 36) = 9.471, p < .001, \eta^2_p = .345$. Under normal illumination both groups performed equally ($t_{18} = -1.964$, ns). When confronted with the experimental light–dark condition, the initial decrease in performance was larger for SAG, as was reflected by the significant difference between FAG and SAG in ILD ($t_{18} = -3.845, p < .01$). As expected, after training, catching performance of both groups increased again after training to a performance level equal to FL ($t_{18} = -2.39$, ns).

2.2.2. Temporal structure of the catch

Analysis revealed a significant condition effect for latency time, $F(2, 36) = 222.522, p < .001, \eta^2_p = .925$. When the light–dark condition was first introduced to the
participants, LT increased significantly compared to catching under normal illumination, and increased even further after training (TLD). Post hoc comparisons revealed significant differences between all light conditions. A group effect ($F(1, 18) = 4.564$, $p < .05$, $\eta^2_p = .202$) and a condition $\times$ group interaction ($F(2, 36) = 3.530$, $p < .05$, $\eta^2_p = .164$) were present as well, indicating that the FAG group had a larger LT than the SAG group in the ILD condition only. Both groups had an equivalent LT in the FL and TLD condition. For movement time, the obtained results were congruent with those of LT: a main effect of condition ($F(2, 36) = 234.489$, $p < .001$, $\eta^2_p = .929$) and condition $\times$ group interaction ($F(2, 36) = 3.351$, $p < .05$, $\eta^2_p = .157$) were present. Under FL, catching movements lasted about 500 ms for both groups. After the light–dark task was implemented, the decrease in MT for FAG was larger as compared to SAG ($t_{18} = 2.245$, $p < .05$). After training, MT of both groups decreased furthermore and reached again equal values of about 277 ms. However, the functional grasping task revealed a significantly lower minimum MT of about 222 ms as compared to the TLD condition ($t_{19} = -7.952$, $p < .001$). No effects were present for grasping time: $F(2, 36) = .296$, ns, for condition; $F(1, 18) = 1.894$, ns, for group;

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Means and standard deviations of all dependent variables as a function of illumination condition, for both the slow and fast adaptation group</th>
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<tbody>
<tr>
<td></td>
<td>FL SAG</td>
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<tr>
<td></td>
<td>FAG</td>
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<tr>
<td>Catch. perf.</td>
<td></td>
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<tr>
<td>Mean</td>
<td>9.70</td>
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<tr>
<td>SD</td>
<td>0.48</td>
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<tr>
<td>LT (ms)</td>
<td>221.9</td>
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<tr>
<td>SD</td>
<td>47.4</td>
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<tr>
<td>MT (ms)</td>
<td>532.1</td>
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<tr>
<td>SD</td>
<td>49.1</td>
</tr>
<tr>
<td>GT (ms)</td>
<td>55.8</td>
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<tr>
<td>SD</td>
<td>7.1</td>
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<tr>
<td>PeakH$_a$ (mm)</td>
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<tr>
<td>Mean</td>
<td>118.7</td>
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<tr>
<td>SD</td>
<td>16.3</td>
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<tr>
<td>D$\times$W (mm)</td>
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<tr>
<td>Mean</td>
<td>340.9</td>
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<tr>
<td>SD</td>
<td>59.4</td>
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<tr>
<td>CoS (%)</td>
<td>108.6</td>
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<tr>
<td>SD</td>
<td>6.3</td>
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<tr>
<td>PVwrist (mm/s)</td>
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<tr>
<td>Mean</td>
<td>2675.4</td>
</tr>
<tr>
<td>SD</td>
<td>238.8</td>
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</tbody>
</table>

Catching performance is expressed as the number of successful catches out of 10.
and $F(2, 36) = .446$, ns, for condition × group. The grasp was initiated about 52.5 ms (±11.3) prior to contact irrespective of light condition.

2.2.3. Kinematic measures

A significant condition effect was present for peak hand aperture ($F(2, 36) = 41.304, p < .001, \eta^2_p = .696$). Post hoc analysis revealed significant differences in PeakHa between all conditions: compared to the FL condition, participants opened their hand wider when catching in the dark. However, after training PeakHa was partly reduced again compared to the ILD condition. Considering the forward displacement of the wrist, an important interaction effect between condition and group was established ($F(2, 36) = 4.811, p < .05, \eta^2_p = 21.1$). Both groups intercepted the ball closer to the body in the TLD condition as compared to catching in normal light, i.e. the position of the wrist at ball-hand contact was located more backward in TLD than FL ($t_9 = 3.372, p < .01$ and $t_9 = 4.299, p < .01$ for respectively SAG and FAG). An important difference in the coefficient of straightness revealed a significant effect of light condition, $F(1.2, 22.3) = 14.533, p < .001, \eta^2_p = .447$ (Huynh-Feldt correction). The wrist followed a more rectilinear trajectory to the place of interception in the LD condition as compared to catching in FL. For peak wrist velocity a condition effect appeared as well ($F(2, 36) = 71.495, p < .001, \eta^2_p = .799$). When catching in the dark, significant higher PVwrist values were present, compared to catching under normal light conditions ($p < .001$). After training the LD task, however, even higher peak wrist velocities were present as compared to the initial dark trials ($p < .01$): mean PVwrist of 3653 mm/s and 4016 mm/s were found for respectively the ILD and TLD condition. Significant higher peak wrist velocities of about 5030 mm/s ± 697 were established during the functional grasping task as compared to the TLD condition ($t_{19} = 10.223, p < .001$).

2.2.4. Variability

Significant condition effects were present for all temporal and kinematic variables included in the present experiment (see Table 2). However, the direction of the effects differed somehow. Compared to the FL condition, within-subject variability for LT and MT increased when catching initially in the dark ($p < .001$), but decreased again after training ($p < .001$). A similar variability pattern was present for GT, $D \times W$ and PVwrist: when confronted with the new light–dark condition, within-subject variability increased compared to movements that were produced in the FL condition ($p < .01, p < .001, p < .001$; for respectively GT, $D \times W$ and PVwrist). After training variability was reduced ($p < .01, p < .05, p < .05$; between ILD and TLD for respectively GT, $D \times W$ and PVwrist), but within-subject variability measures were still higher as compared to the FL condition ($p < .05, p < .01, p < .01$; between FL and TLD for respectively GT, $D \times W$ and PVwrist). In contrast, a decreasing variability pattern was found for PeakHa and CoS when catching in the dark. Within-subject variability of PeakHa appeared to be significantly lower, only in the TLD condition compared with the FL condition ($p < .01$); while CoS showed a lower variability in both dark conditions compared to FL ($p < .01$).
The aim of this experiment was to investigate the adaptation process of the human perceptuo-motor system to changing perceptual-motor constraints. Although all participants quickly mastered the catch-in-the-dark task, differences in the duration of this learning process were apparent. Although a satisfying performance of 8.3 out of 10 trials was accomplished after training, mean catching outcome could not equal performance under the full light condition. Nevertheless, the performance obtained in the LD condition after only a few trials is very impressive and highlights the adaptive capacities of the agents.

To cope with the informational/perceptual constraint of the light–dark paradigm, LT was deliberately prolonged. More precisely, participants delayed their movement initiation to 277 ms (±32 ms) on average before ball-hand contact, which approximates Whiting’s COP quite well. By consequence, a change in temporal structure of the catch emerged: postponing the initiation of the catch engenders a shortening of MT. Since less time became available for executing the catch, compensation strategies were adopted similar to those that emerge when catching under increasing temporal constraints (Laurent et al., 1994; Mazyn et al., 2006). Extra time for movement execution was conquered by catching the ball more backward, and accordingly stretching the flight time of the ball, while leaving the amount of visual information unchanged. Moving the hand straight onto
the interception point engendered also a less time consuming catching movement. However, a faster displacement entails a loss in spatial accuracy (Fitts, 1954; Schmidt, Zelaznik, Hawkins, Franks, & Quinn, 1979), which was compensated by increasing peak hand aperture: such adaptation facilitated successful catching by enhancing the error tolerance in spatial accuracy.

The observed difference in adaptation speed to the LD paradigm between FAG and SAG was not only visible in the catching performance, but in the kinematics as well. SAG showed already persistent adjustments in the spatial characteristics of the movement (PeakHa and trajectory of the wrist) within the initial 10 attempts under LD. Conversely, the aspects that involve temporal adaptation (LT, MT, retreat of the interception point) show only a partially change towards the features of the trained movement at first, and evolve further during practice. While SAG first adjusts at the spatial level before temporal changes are made, FAG adapts immediately on both spatial and temporal levels. The spatial-temporal sequence in acquiring kinematic characteristics at different times during practice in SAG is in line with the existing literature (Magill, 2004; Marteniuk & Romanow, 1983).

From this first experiment the suggestion can be made that humans can easily switch between control mechanisms (from on-line under normal illumination towards a planning mode in the LD condition), depending on the constraints imposed. An examination of the velocity profiles of hand aperture is in line with such a shift between control mechanisms (Fig. 2). When catching in FL, an initial increase in hand aperture was apparent, followed by a second peak in hand aperture velocity at the end of the movement, which might reflect an online adjustment (Fig. 2a). In the LD condition, however, no such adjustment was encountered in the velocity profile: after initiation of hand opening, a constant opening velocity was maintained until the grasp started (Fig. 2b). In addition, an asymmetric velocity profile of the transport phase indicates the use of continuous regulation in goal directed aiming (Elliott, Helsen, & Chua, 2001). When catching in the dark, peak wrist velocity occurred at 50% of MT, i.e. halfway the unfolding movement. On the contrary,
only 30% of MT had elapsed in the FL condition when peak wrist velocity arose. Hence, the greater proportional time after peak velocity of the catching movement, allowing adjustments, points to the use of an on-line control mechanism under FL, which is not the case in the LD conditions.

The within subject variability measures also suggest a search for a new movement solution when shifting from FL to LD. Except for the space related kinematic measures (PeakHa and CoS), an increase in variability was present in ILD, compared to performance in FL. After reaching the criterion for acceptable skill level in the dark (TLD), variability measures were again significantly reduced, reflecting a regain of stable performance after training. This indicates that participants experience the LD condition more or less as a new task at first, which implicates searching for the right motor solution to meet the task requisites. On the contrary, within subject variability of the spatial variables PeakHa and CoS initially decreased in the LD condition (ILD), compared to FL. After training (TLD), variability was even further reduced. The positional uncertainty brought about by the darkness could explain this immediate reduction of the within subject variability of these spatially related variables. The light–dark paradigm strains the adaptation mechanisms to the limit, and hence compels the spatial variables at once towards uniformity. Due to a lack of information during movement to tune the catch onto, the hand keeps opening further to a more or less maximal width and the wrist continues its initial path in straight line where the catches expects the ball to arrive. When initially confronted with the light–dark situation, the wrist already travels to the future place of interception without much detour, even when the backward shift of the interception point has not occurred yet.

The purpose of the functional grasping task was to give an estimation of how fast the participants could perform a catching movement in general. The minimum MT as well as the PVwrist has demonstrated that movements can be produced that are both shorter and faster, compared to the catching movements as performed in the LD condition. This incites the suggestion that the initiation of the catching movement might be determined by perceptual rather than motor constraints. However, statements regarding the nature of the triggering of movement onset and the limits of COP need further elaboration. The possibility exists that the MTs found in the present experiment only stem from the specific experimental set-up (e.g. ball velocity or flight time). Therefore, the aim of the second experiment was to extend these findings to situations with varying temporal demands.

3. Experiment 2

3.1. Methods

3.1.1. Participants

The 10 participants of the fast adaptation group from the first experiment, plus two extra participants – who also achieved seven catches out of 10 within maximal two practice blocks of 10 trials –, took part in the second experiment. All participants (seven males and five females, mean age 22.3 ± 2.3 years) were highly skilful catchers and had normal or corrected-to-normal vision. All participants preferred to use their right hand for ball catching. After a clarification of the task and procedure, participants gave their written consent to volunteer for the present experiment that was approved by the Ethics Committee of the Ghent University Hospital.
3.1.2. Task and apparatus

The task, apparatus and experimental set-up were identical to experiment 1. In the present study that took place one week after experiment 1, participants had to catch balls under the two illumination conditions (FL and LD) at two additional approaching speeds. This resulted in a total data set of three ball speed conditions: 8.7, 10.5 and 13.2 m/s, corresponding to flight times of respectively 965, 800 and 636 ms.

3.1.3. Procedure

With each new ball speed, the testing trials were preceded by five acclimatization catches, which allowed the experimenters to check whether the launching angle and height of the ball machine was adjusted properly. First, 10 successful catches at both ball speeds were performed under FL. Next, the participants performed at the LD condition: the LD condition was practiced in blocks of 10 trials, until a criterion of seven successful catches out of 10 was achieved. 3D-kinematics of the 10 catches in the FL condition, and 10 successful trials after reaching the criterion in the LD condition were recorded with the Qualisys motion capture unit. The sequence of ball speeds at both illumination conditions was randomised to exclude the effects of presentation order.

3.1.4. Data acquisition and dependent measures

Camera set-up, placing of the reflective markers and only five relevant dependent variables were taken from experiment 1: LT, MT, PeakHa, $D \times W$ and CoS. Since the present experiment focussed on the nature of the trigger for movement onset and the magnitude of the COP, enabling successful catching, only data from successful trials were included in the kinematic analysis. Therefore catching performance was not considered. In addition, the changes in movement coordination were studied as well, by calculating Cross-correlation coefficients between 3D angles of elbow and hand (CCEH). The elbow angle is defined as the angle that arises between the markers of respectively processus styloideus ulnaris, processus choroideus 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 external face of the distal phalanx of the pollex. Cross-correlations express time-relationships between the components of the moving system, e.g. how two angles evolve in time against one another. The absolute value of the coefficient represents the strength of the coupling. A cross-correlation coefficient nearer to 1 represents a closer linkage, where a coefficient approximating zero signifies that joints move more independently from one another (Ko, Challis, & Newell, 2003; Mazyn et al., 2006; Temprado, Della-Grasta, Farrell, & Laurent, 1997; Vereijken, van Emmerik, Whiting, & Newell, 1992).

3.1.5. Data analysis

A 3 (ball speeds) $\times$ 2 (light conditions: FL and LD) repeated measures ANOVA analysis of variance was carried out on all variables. For CCEH, the cross-correlation coefficients were first determined for each separate trial, and then averaged per participant for each condition of ball speed and illumination. These mean cross-correlations were submitted to a repeated measures ANOVA analysis of variance to quantify the possible changes in coordination pattern. In case of violation of the sphericity assumption in repeated measures ANOVA, the Huynh-Feldt correction was applied.
Post hoc LSD-tests were used to further analyse the main effects, while for the interaction effects paired samples *T*-tests were conducted. An alpha level of .05 was used for all statistical tests and the size of the effect was reported by means of the partial Eta squared ($\eta^2_p$).

### 3.2. Results

Main effects on ball speed and light condition were found for all variables. However, since these main effects were accompanied by important interactions, only these interaction effects will be further elaborated. A strong interaction between ball speed and light condition was present for both LT and MT (see Table 3). While LT hardly decreased over ball speeds in FL, a substantial reduction of LT was found when catching in the dark. In contrast, the decrease in MT with increasing ball speed under FL exceeded the decrease in MT in the LD condition, where only a minor speed effect was present (Fig. 3). The minimum MT necessary to execute such catching movement (221 ms, as measured from the functional grasping task) was significantly shorter than the MTs in the LD condition ($t_{11} = -27.130, p < .001$; $t_{11} = -27.138, p < .001$ and $t_{11} = -27.142, p < .001$; for respectively the 8.7, 10.5 and 13.5 m/s condition in LD).

For all three spatial variables (PeakHa, $D\times W$ and CoS), significant speed × light interactions were found as well (see Table 3). When catching under normal illumination, PeakHa increased with increasing ball speed. In the LD condition, no speed effect could be detected. Equal maximal hand apertures were found for all ball speeds, and these

### Table 3

Means and standard deviations of all dependent measures for the three ball velocities (m/s) under both light conditions as well as statistical data for the interaction effects between light condition (light) and ball speed (speed)

<table>
<thead>
<tr>
<th></th>
<th>Full light (8.7 m/s)</th>
<th>Light-dark (8.7 m/s)</th>
<th>Light × Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LT (ms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>362.7</td>
<td>261.1</td>
<td>242.7</td>
</tr>
<tr>
<td>SD</td>
<td>56.0</td>
<td>61.5</td>
<td>26.6</td>
</tr>
<tr>
<td><strong>MT (ms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>556.6</td>
<td>494.5</td>
<td>363.7</td>
</tr>
<tr>
<td>SD</td>
<td>56.5</td>
<td>60.0</td>
<td>28.2</td>
</tr>
<tr>
<td><strong>PeakHa (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>114.2</td>
<td>113.4</td>
<td>125.0</td>
</tr>
<tr>
<td>SD</td>
<td>14.6</td>
<td>8.9</td>
<td>14.7</td>
</tr>
<tr>
<td><strong>$D\times W$ (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>300.2</td>
<td>312.3</td>
<td>282.7</td>
</tr>
<tr>
<td>SD</td>
<td>49.1</td>
<td>48.7</td>
<td>37.9</td>
</tr>
<tr>
<td><strong>CoS (%)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>109.2</td>
<td>108.0</td>
<td>105.1</td>
</tr>
<tr>
<td>SD</td>
<td>4.3</td>
<td>4.9</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>CCEH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>-.20</td>
<td>-.16</td>
<td>-.60</td>
</tr>
<tr>
<td>SD</td>
<td>.48</td>
<td>.48</td>
<td>.30</td>
</tr>
</tbody>
</table>

*a Huynh-Feldt correction.*
appeared to be significantly wider as compared to PeakHa in the FL condition \(t_{11} = 6.926, p < .001\); \(t_{11} = 6.960, p < .001\) and \(t_{11} = 2.848, p < .05\) between FL and LD for respectively the 8.7, 10.5 and 13.2 m/s ball speed condition). The speed effect that was present under FL for \(D \times W\), perished as well when catching in the dark. In FL, the wrist is located closer to the body under the highest ball speed as compared to both lower ball speeds. In LD the interception point was retreated to the same extent irrespective of ball speed and was positioned much closer to the catchers’ frontal plane as in the FL condition. This strategy yielded a significant gain in the flight time of the ball in all speed conditions: 12 ms \(t_{11} = 3.249, p < .01\), 12 ms \(t_{11} = 4.587, p < .01\) and 5 ms \(t_{11} = 2.164, p = .053\) between FL and LD for respectively the 8.7, 10.5 and 13.2 m/s ball speed condition. Finally CoS decreased with increasing ball speed in FL, while for the LD condition similar CoS measures were present for the three ball speeds. The rectilinearity of the wrist trajectory under the highest ball speed in FL approximated CoS under LD.

At coordination level, a speed \(\times\) light interaction was also found for CCEH (see Table 3 for statistical data). Under normal illumination absolute cross-correlation values were higher at the highest ball speed condition, compared to the slower ball speeds. In the LD condition even higher CCEH measures were found. Irrespective of ball speed condition, cross-correlations of about .820 were observed between the angle of hand aperture and elbow. These changes in coordination pattern, as expressed by the cross-correlations, are visualized in Fig. 4. The angle-angle plots represent time normalised and averaged data over all trials and participants for each ball speed and illumination condition. From Fig. 4b, the more synchronized elbow-hand coordination when catching in the dark can be perceived, compared to the clearly phased pattern (Fig. 4a) at the lower ball speed in full light (see also Mazyn et al., 2006; for the interpretation of angle–angle plots). Elbow-hand coordination at the highest ball speed condition under normal illumination is rather situated somewhere in between.

### 3.3. Discussion

The main objective of this second experiment was twofold. On the one hand it was examined whether movement initiation is perceptually triggered or rather motor based.
On the other hand, it was verified whether the COP of 280 ms that was found in experiment 1 was inherent to the specific ball velocity and flight time that was used, or whether this intrinsically driven COP could be generalized to varying ball speed conditions.

From this second experiment it was found that, when catching in the dark, MT was reduced to similar properties irrespective of ball speed condition. The movement times of 311, 281 and 270 ms were measured for respectively the 8.7, 10.5 and 13.2 m/s conditions, which correspond with respectively 34, 37 and 44% of the total ball trajectory that was invisible. This finding confirms the formerly proposed magnitude of the COP (Sharp & Whiting, 1975; Whiting & Sharp, 1974). However, the small but significant effect of ball speed indicates that the COP is still sensitive to the imposed temporal constraints.

The functional grasping task showed that participants did not produce catches against their motor limits when performing in the LD condition. If the movement onset would be purely motor driven, the participants would postpone movement initiation with another 55 ms, i.e. 20% of the MT under the highest ball speed condition. So these results argue again for a movement initiation time being the result of perceptual rather than motor constraints.

Another remarkable finding was the strong interaction between ball speed and illumination condition for all of the dependent measures. More specifically, an effect of ball velocity was present when catching under normal illumination. A decrease in MT, a backward shift of the interception point, a more rectilinear wrist trajectory and an enlarged hand aperture were found across increasing ball speed conditions. In fact, these speed effects that appeared in the full light condition were expected and are in line with the earlier work of Laurent et al. (1994) and Mazyn et al. (2006). However, these speed effects that were found in FL disappeared when catching in the dark. The informational constraints of the task seem to compel the catching movement into a definite movement pattern, regardless of the additional temporal constraints imposed on the task. To meet the imposed perceptual-motor constraints, a movement with similar kinematic features was produced under the three different ball speed conditions. This finding pleads strongly for the use of a planning mode when catching in the dark.

Fig. 4. Angle-angle plots of time series of elbow angle against angle of hand aperture for the three ball speed conditions under full light (a) and light–dark (b) illumination. For each ball speed condition, data of the time series were first time-normalised, and subsequently averaged over all participants. Movement initiation is situated at the left end of the graphs.
As already mentioned, these subtle kinematic adjustments, that were observed when catching in the dark, resemble closely to those appearing when catching balls that approach at high velocities (Laurent et al., 1994; Mazyn et al., 2006). The informational constraint in the present experiment forced the catcher to behave as in a highly temporal constrained situation, a suggestion that was also supported by the coordination pattern of hand and elbow (CCEH). Moreover, the results of the functional grasping task, which captured the functional speed limits of the motor apparatus, demonstrate that the obtained kinematic adaptations in the LD condition were not regular ceiling effects. In the experiment by Mazyn et al. (2006), where balls were launched at speeds ranging from 8.6 to 19.7 m/s, an attempt was made to map the coordination pattern of one-handed catching. Their main finding was a gradual shift from a phased movement at low ball speeds towards a simultaneous coordination at the highest ball speeds. The informational constraints in the present study induced a similar reconversion in coordination from catching under FL to catching in the LD condition, as was shown by the strong increase of CCEH. The angle-angle plots (Fig. 4) support this finding by visualizing the evolution of elbow angle against the angle of hand aperture. Under normal continuous illumination, the main elbow flexion precedes the opening and closing action of the hand. However, at the highest ball speed condition, the clear distinction between both phases already fades to some extent. This is caused by the higher temporal constraint at the 13.2 m/s condition (see Mazyn et al., 2006) and is also expressed by the higher cross correlation values, compared to the 8.7 and 10.5 m/s conditions. After having adapted to the light–dark situation both angles change optimally synchronised in all ball speed conditions, which indicates that a new and stable movement solution has emerged.

4. General discussion

The first main question that was addressed by the present experiment was how much movement time catchers prefer if no visual information is available after movement onset. The specific set-up of the light–dark condition (coupling movement onset and illumination) was intentionally chosen to face the participants with a trade-off between ‘information gathering time’ and ‘effective catching time’. In the present study latency times ranging from 240 to 360 ms (for the 8.7 to the 13.2 m/s ball speed conditions) were present in the FL condition. According to the findings of Sharp and Whiting (1975), catching performance is optimal when a viewing period of at least 240 ms and a dark period that did not exceed 280 ms are available. If participants would produce a similar catching movement in the LD condition as they did under FL, enough information would have been available, i.e. the viewing period would still be longer than the required 240 ms. However, since persistence of visual information is limited in time (Elliott, Zuberec, & Milgram, 1994; Olivier et al., 1998), the dark period (ranging between 550 and 360 ms across increasing ball speed conditions) would be too long to allow a reliable prediction of place and time of the arrival of the ball. The results of the present experiments indicate that the participants are driven towards similar COP’s of about 280 ms (as originally proposed by Sharp & Whiting, 1975), when allowed to choose the amount of information they want to use/disregard before ball-hand contact themselves. Together with the observation that the catch can be executed even faster than the subjects did at the highest ball speed, this indicates that movement onset is more likely to be triggered by perceptual constraints than by limitations to the motor system.
The second main question concerned the changes in movement execution apart from postponing the initiation of the catch. In the LD condition, the participants adapted not only by delaying movement initiation but also by applying more subtle time and space buying strategies. Extra time for movement execution was gained by a retreat of the place of ball-hand contact, and by a more rectilinear transport phase towards that interception point. Shifting the interception point backwards, i.e. closer to the body, entails a twofold gain in time: the place of interception is located closer to the starting position of the hand (less distance to travel for the wrist) and an extension of the ball trajectory. Even though this creation of extra time in favour of information uptake is not essential (an adequate viewing time of about 479 ms would still be available), this extension of the ball trajectory provides information of the ball closer to the catcher and could facilitate a more accurate prediction of the ball’s trajectory. This backward shift of the interception point was achieved by a retreat of the wrist as well as by the elbow and shoulder. Moving the wrist along a straighter course might reduce travelling time as well. Next to these time buying means, a space buying strategy was also introduced into the catching movement: a significantly larger PeakHa was attained during the catch, which enlarged the contact surface with the ball. The larger hand aperture entails a twofold compensation: (1) for the increase in spatial uncertainty involved when catching in the dark, and (2) for the decrease in movement accuracy engendered by the faster execution of the catch (Fitts, 1954; Schmidt et al., 1979).

From the results of the functional grasping task one might presume the triggering of movement onset not to be motor driven. This grasping task consisted of producing a grasping movement towards a stationary tennis ball as fast as possible. The starting position of the hand and location of the ball was deliberately chosen so that a movement, very similar to the real catching movement, would be provoked. All participants from both experiments could produce a faster movement in the grasping task as they actually performed in the light–dark condition: MTs of 222 and 277 ms and peak wrist velocities of 5030 mm/s and 4016 mm/s were found for respectively the functional grasping task and catching in the TLD condition in experiment 1. From experiment 2, significant shorter minimum MT were also found when compared to the MTs under each of the ball speed conditions in LD. So from both experiments evidence was found that argues for a perceptually triggered catching movement: the catcher waits just as long as he/she considers to have collected sufficient visual information for achieving a successful catch. However, one must consider that producing a movement near the boundaries of ones motor capacities (i.e. when movement initiation would be further delayed), is neither favourable, since movement accuracy would suffer essentially.

When raising the issue of motor control underlying catching movements in both visual conditions, it is clearly that a shift from on-line control in FL towards a planning mode in LD has occurred. This open-loop control mechanism is not only very efficient; it also emerges very rapidly, i.e. after 15 trials on average for the fast adaptation group. Furthermore, the additional time- and space buying strategies produced by the catchers in the LD condition are probably designed to make this control mechanism more efficient. It seems indeed easier to be successful in the planning of a movement when the spatial tolerance is high (enlarged hand aperture), and when a short movement (interception located closer to the body) along a rectilinear path (more rectilinear wrist trajectory) can be produced. A similar shift in control mechanisms was also found in a study where participants were grasping for stationary objects (Heath, Westwood, & Binsted, 2004).
In this study, speeding up the execution of the catch is the result of trading off between gathering sufficient visual information and still having enough time for a more or less comfortable movement execution, this trade-off point being approximately 280 ms before ball-hand contact. From another point of view, a faster movement is accompanied by an increase in temporal consistency and a decrease in spatial accuracy (Brenner, De Lussanet, & Smeets, 2002; Fitts, 1954). It might be that spatial accuracy decreases to such an extent beyond this 280 ms that the benefit of a higher temporal consistency is overruled. Finally, speeding up the movement might also be beneficial because it shortens the period during which visual information must be held in memory. The persistence of visual information is rather short (Olivier et al., 1998), so any means to reduce the retention period might contribute to a successful catch.

In sum, the findings of the present experiment emphasize the exceptional ability of the human perceptuo-motor system to easily adapt its actions depending on the imposed task constraints, even in a less natural setting.

References


