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Spatial and Temporal Adaptations That Accompany Increasing Catching Performance During Learning

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ABSTRACT. The authors studied changes in performance and kinematics during the acquisition of a 1-handed catch. Participants were 8 women who took an intensive 2-week training program during which they evolved from poor catchers to subexpert catchers. An increased temporal consistency, shift in spatial location of ball–hand contact away from the body, and higher peak velocity of the transport of the hand toward the ball accompanied their improvement in catching performance. Moreover, novice catchers first adjusted spatial characteristics of the catch to the task constraints and fine-tuned temporal features only later during learning. A principal components analysis on a large set of kinematic variables indicated that a successful catch depends on (a) forward displacement of the hand and (b) the dynamics of the hand closure, thereby providing a kinematic underpinning for the traditional transport–manipulation dissociation in the grasping and catching literature.

Keywords: catching, kinematics, motor learning, transfer

Catching is a skill that is omnipresent in life from childhood on. Catching a ball requires coordination between the limbs, which enables the performer to produce an appropriate movement pattern and coordination between the motor action and environmental events, that is, the trajectory of the ball. From that point of view, catching is an interesting task that allows movement scientists to increase their knowledge of perceptual–motor functioning (e.g., Bennett, van der Kamp, Savelsbergh, & Davids, 2000; Mazyn, Lenoir, Montagne, & Savelsbergh, 2004; Rushton & Wann, 1999; van der Kamp, Savelsbergh, & Smeets, 1997). However, studies that have focused on how to learn one-handed catching are scarce and feature (a) a relatively moderate number of acquisition trials and (b) a primary interest in changes at the behavioral level (i.e., catching performance; Bennett, Button, Kingsbury, & Davids, 1999; Bennett, Davids, & Woodcock, 1999; Lyons, Fontaine, & Elliott, 1997; Savelsbergh & Whiting, 1992; Whiting, Savelsbergh, & Pijpers, 1995). To our knowledge, in no single study have researchers concentrated on the kinematic changes that accompany participants' increasing catching performance during learning.

Catching is a fairly easy task when performers have ample time to adjust the ongoing movement to the spatiotemporal characteristics of the ball flight, because several coordination modes can lead to a successful catch. For example, a person can execute transportation of the catching hand and the grasp itself in succession or simultaneously. At high ball speeds, however, the number of appropriate movement solutions decreases because of increased temporal constraints (Marteniuk & Romanow, 1983). The time available to bring the hand into the ball trajectory and to accurately time the closure of the hand around the ball decreases, making the task more difficult to achieve (Mazyn, Montagne, Savelsbergh, & Lenoir, 2006).

With regard to the spatial and temporal aspects of a motor skill, investigators have suggested that spatial changes (displacement) in movement execution precede temporal changes (velocity and acceleration) during the acquisition process (Magill, 2004). Fuchs (1962) showed that learners increasingly give more weight to velocity information with increasing practice, whereas they attend less to positional (amplitude) information. In a discrete sequential movement task, Marteniuk and Romanow (1983) found that participants learned the spatial characteristics of the criterion path first, whereas they improved their velocity and acceleration

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patterns only later in the learning process. With respect to catching, Alderson (1974) noted that through learning and development, children are first successful in the spatial positioning of the hand into the ball trajectory, resulting in the ability to achieve ball–hand contact. Later, temporal aspects become more refined, leading to a successful grasp and hold of the ball. Glover (2004) recently proposed a control model that is compatible with such a relative independence of spatial and temporal aspects.

Many researchers have presented results that contradict such an artificial separation of temporal and spatial features in movement control and learning. The results of several experiments have shown that spatial and temporal characteristics of interceptive movements are somehow interwoven and therefore cannot be considered fully separate entities of the motor action (e.g., Caljouw, van der Kamp, & Savelsbergh, 2006; Davids, Bennett, Handford, & Jones, 1999). For example, in juggling, novices face a primarily temporal problem: how to catch, pass, and throw a set of balls at a high pace. Beek and Turvey (1992) showed that the solution lies in the spatial adaptation of the tossing action. However, it is plausible that learners achieve significant coordination changes mainly in the very early stages of learning a new skill (as in Beek and Turvey's study), whereas they achieve performance improvement in later stages by attuning better to the specific demands of the task, without the need for a complete reorganization of the movement (Gentile, 2000). In this study, we focused on changes in kinematics of a task that participants had already mastered in its simplest, temporally unconstrained form. Thus, we primarily expected changes in the fine-tuning of the catch, rather than at the coordination level (Newell, 1991). Nevertheless, those changes are very important because of the constraints in unimanual catching: Even the smallest error in the temporal execution of the catch, the spatial execution of the catch, or both can lead to a miss. Similarly, a small change in temporal or spatial characteristics of the catch can significantly increase an individual's catching performance (i.e., the number of balls caught).

In this study, our first aim was to document the kinematic changes that accompany performance gain during the learning of a one-handed catch under demanding temporal constraints. We therefore imposed an extensive acquisition scheme of almost 1,500 trials. Because most people are able to catch a ball at low speeds, we assumed that our participants had a basic coordination pattern for a one-handed catch. We therefore did not expect major changes in intralimb coordination in this study. Following the results of Marteniuk and Romanow (1983), we hypothesized (a) that when we imposed a new constraint in the form of a specific ball speed, the catchers would attune their action primarily at the spatial level and (b) that their temporal attunement to the task constraints would occur only later in the learning process. Moreover, by also considering transfer effects to other ball speeds, we aimed at gaining more insights not only into the spatiotemporal changes that accompany learning but also into the plasticity of the underlying control mechanisms.

On a related issue, an extensive learning study on catching implies that a large number of successful and unsuccessful catches are comparable. Such a comparison allows the researcher to identify the essential kinematic features of the catching action that are primarily responsible for a catch or a miss.

Method

Participants

We assessed initial catching ability in a large group of candidate participants (N = 82) who caught with their preferred hand tennis balls that we launched at a speed of 10.8 m/s. In advance, we gave five acclimatization trials. Participants who succeeded in fewer than 10 out of 20 trials qualified to take part in the study. In addition to initial catching performance, we assessed visual acuity by using the Snellen E chart, and we measured stereo acuity with the Graded Circle Test (from the Random Dot Stereo Butterfly test battery; Stereo Optical Company, Chicago). We eventually selected 17 female poor catchers (M age = 22.6 years, SD = 4.8 years), who scored on average 3.2 (± 2.0) successful catches out of 20 on the screening test, to take part in the present study, and we subsequently assigned 9 of them to the control group (CoG) and 8 to the training group (TrG). All participants had normal or corrected-to-normal visual acuity and normal stereo acuity. We administered screening tests a few weeks before the start of the experiment so participants would not become familiar with the specific ball-velocity condition. After we informed them about the requirements of the experiment, all participants gave written consent to volunteer for this study. The Ethics Committee of the Ghent University Hospital approved the study protocol.

Task and Apparatus

As in the screening test, we asked participants to catch yellow midpressure tennis balls with their preferred hand. The participants stood in a comfortable starting position, with their arms and hands relaxed beside the body and the right foot placed on a marking on the floor. Balls were projected at speeds of 10.8, 13.1, and 15.5 m/s by a Singly Promatch launching machine (MUBO b.v., Gorinchem, The Netherlands) from a distance of 8.4 m from the participants' frontal plane. We used an optoelectric device mounted at the exit of the launching apparatus to detect the time of ball departure. We used fixed launching angles of 25.6°, 22.0°, and 18.1°, respectively, for the 10.8-, 13.1-, and 15.5-m/s ball-speed conditions so that all balls reached participants in an imaginary circle of 30 cm diameter with its center approximately 15 cm above the shoulder of the catching arm. In addition, we adjusted the launching height of the ball to participants' body height by lifting the entire launching device to keep the flight trajectories of the ball similar from the viewpoint of each of the participants.

We attached a switch to the lateral side of participants' thigh. The switch had to be pressed with the thumb of the catching hand before each trial. Release of the switch electronically registered and marked the initiation of the catching movement. Participants used earphones that blocked the noise of the launching device and therefore prevented anticipation of the initiation of the catch. However, participants could somehow anticipate because the ball was visible approximately 20 ms before the launch, an interval that was similar for all ball speeds.

Procedure

We subjected each group (CoG, TrG) to three test sessions (pretest, posttest, retention test) that consisted of three blocks of 30 trials, one block in each of the three ball-speed conditions. We randomized the sequence of ball speeds over all sessions and participants. Before each block, we provided 3 acclimatization trials, which allowed us to verify whether the launching device was properly adjusted to participants' height. We implemented pretest (PrT) and posttest (PoT) with an interval of 15 days, and we conducted the retention test (ReT) 10 weeks after PoT. Between PrT and PoT, the TrG went through an intensive training program: They completed eight training sessions of 180 trials each, presented in blocks of 30, at a ball speed of 13.1 m/s (see Figure 1). On Day 8, the TrG performed an additional intermediate test session (ImT) consisting of 30 trials with a ball speed of 13.1 m/s. Each training session and the ImT lasted about 30 min. The other test sessions lasted about 90 min.

Data Acquisition

During test sessions, we recorded kinematic data of all trials with a three-dimensional (3D) motion capture system (Qualisys, Gothenburg, Sweden) at 240 Hz. A group of eight infrared cameras captured the movements of nine reflective markers that we attached with double-sided cloth tape on the processus coracoideus of the scapula, epicondylus lateralis and medialis of the humerus, processus styloideus of radius and ulna, caput metacarpale of the digitus medius, and the external face of the distal phalanx of the thumb and the index finger of the catching arm and hand. We placed a marker behind the participant, 9.5 m from the ball projection machine. That marker served as a reference point that enabled us to determine the exact position of the catcher. After a successful catch, the participants dropped the ball into a basket and returned the hand to the initial position. In the case of a failure, participants returned the hand to the initial position immediately. The experimenter immediately registered the outcome of each trial as a catch, touch, or complete miss. Because we registered only 0.5% complete misses, we grouped touches and misses together and considered them as misses against the catches when we assessed catching performance. For a backup, we set up a Quick Cam Pro 4000 Webcam (Logitech, Freemont, CA) to film all trials laterally at 30 Hz. We did not collect kinematic data from the training sessions. Therefore, we conducted training trials without switch and markers, and we registered only performance outcome.

Dependent Measures

We assessed the general learning process by evaluating participants' catching performance during test sessions (i.e., the number of successful catches out of 30 throws for each ball-speed condition) and training sessions (i.e., the mean number of successful catches from the six blocks of 30 trials). Next to catching performance (CP), we considered latency time (LT; in ms) and movement time (MT; in ms) for all catches from the test sessions. We defined *LT* as the time elapsed between the departure of the ball and the moment when the participant released the switch. We defined *MT* as the time between movement onset (release of the switch) and ball–hand contact.[1] We calculated intraparticipant standard deviation on LT and MT to assess the variability of the catching movement.

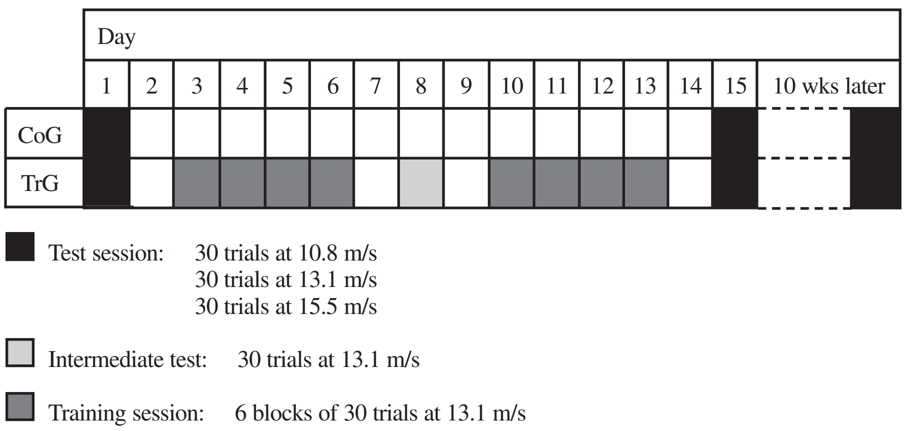

FIGURE 1. Schematic representation of the experimental design. CoG = control group; TrG = training group.

We also conducted a full kinematic analysis of Trials 11–20 of each ball-speed block from the test sessions. We filtered the obtained 3D data of those trials at a cutoff frequency of 10 Hz with a second-order recursive Butterworth filter. We calculated velocities and angles from the time series of coordinates to derive the dependent variables. We analyzed an elaborative spectrum of variables (see Mazyn et al., 2006). However, most of the explored variables did not significantly change during the acquisition phase or the retention period. Therefore, for the readability of this article, we present only the following variables of interest.

1. *Grasping time* (GT; in ms): the time elapsed from the moment the hand-opening velocity turned negative after reaching maximal hand aperture until ball–hand contact.
2. *Forward displacement of the wrist, elbow, and shoulder* (D*x*W, D*x*E, D*x*S, respectively; in mm): the linear distance between the positions of the wrist, elbow, and shoulder, respectively, at the initiation of the catching movement and ball–hand contact along the anteroposterior axis (*x* axis).
3. *Peak wrist velocity* (PeakWv, in mm/s): the maximum velocity the wrist attained during the catching movement.

Data Analysis

We conducted separate repeated measures analyses of variance (ANOVAs) to investigate (a) the effects of the training program on catching performance and kinematics, (b) the profile of the learning process within the TrG, and (c) the effects of transfer to lower and higher ball-velocity conditions. We conducted post hoc comparisons for the retrieved main effects by using a least significant difference test, and we further analyzed interaction effects by using paired- and independent-samples *t* tests. We set the level for statistical significance at .05 and calculated partial eta-squared (η_p^2) to measure effect sizes. We also conducted a principal component analysis (PCA) on all individual trials to examine the kinematic factors that are related to the outcome of the catching movement.

Results

Effects of Training on Catching Performance and Kinematics

To study the effects of the training program, we applied a 3 (test: PrT, PoT, ReT) × 2 (group: CoG vs. TrG) ANOVA with repeated measures on the first factor on all considered variables. Those analyses included only the trials that participants performed at the training speed of 13.1 m/s.

With respect to catching performance in the 13.1-m/s speed condition (see Figure 2), we found a significant interaction effect between test and group, $F(2, 30) = 24.261$, $p < .001$, $\eta_p^2 = .618$. Whereas CP of the CoG did not improve, CP of the TrG increased significantly over time. Their increased performance was still preserved after 10 weeks. Means and standard deviations of all dependent variables are shown in Table 1. Because LT

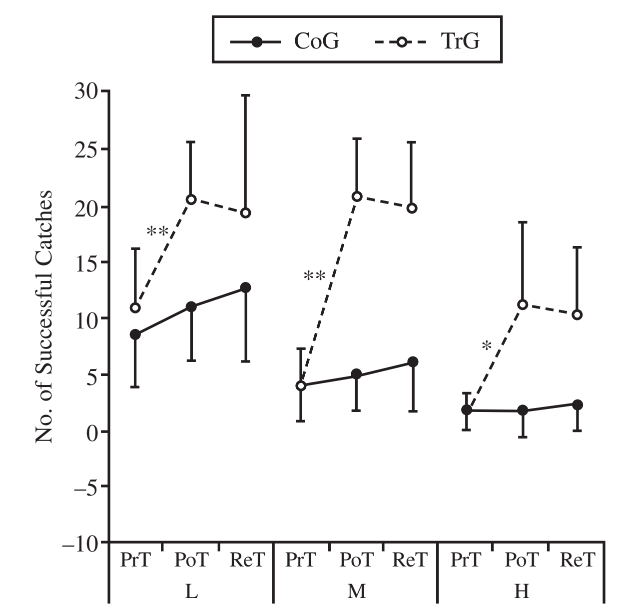

FIGURE 2. Number of successful catches at the pretest, posttest, and retention test (respectively, PrT, PoT, and ReT) for the training group (TrG) and the control group (CoG) under each of the three ball-speed conditions. L, M, and H, respectively, were the 10.8-, 13.1-, and 15.5-m/s ball speeds. Significant gains in performance are indicated with asterisks. $^{*}p < .05$. $^{**}p < .001$.

and MT are closely related, we discuss further in this article only MT. For MT, we found no main test effect, $F(2, 30) = .409$, *ns*, $\eta_p^2 = .027$, or Test × Group interaction, $F(2, 30) = 1.106$, *ns*, $\eta_p^2 = .069$, at the training speed (13.3 m/s). However, within-participant variability in MT (*SD*MT) did show a significant Test × Group interaction, $F(2, 30) = 8.007$, $p < .005$, $\eta_p^2 = .348$. After training, *SD*MT of the TrG was significantly reduced, and the reduction persisted through the retention test, whereas *SD*MT of the CoG remained unaltered.

Analysis of the forward displacement of the interception point revealed Test × Group interactions, resepctively, for D*x*W, $F(2, 30) = 7.100$, $p < .005$, $\eta_p^2 = .321$; D*x*E, $F(2, 30) = 6.879$, $p < .005$, $\eta_p^2 = .314$; and D*x*S, $F(2, 30) = 6.676$, $p < .005$, $\eta_p^2 = .308$. Although the CoG showed a significant retreat of the wrist, elbow, and shoulder over the test sessions, the TrG moved the interception point more forward after training in comparison with its location in the PrT. Participants achieved forward displacement at the three joint levels, and that displacement was still present at the ReT. We also found a nearly significant Time × Group interaction for PeakWv, $F(2, 30) = 3.173$, $p = .056$, $\eta_p^2 = .175$. PeakWv of the TrG tended to be higher after training and at the ReT than in the PrT. For the CoG, PeakWv tended to be lower, $p = .086$, than that of the TrG at the PoT, but it increased between PoT and ReT. We found no effects for GT. Mean GT approximated 67.3 ms and remained unaltered across the test sessions.

TABLE 1. Means and Standard Deviations of Kinematic Variables in the Pretest (PrT), Posttest (PoT, and Retention Test (ReT) for Both Groups at the Training Speed

	CoG test session						TrG test session								
	PrT		PoT		ReT		PrT		ImT		PoT		ReT		
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*p*
CP (no. out of 30)	4.0	3.2	5.0	3.4	6.1	4.4	3.9	3.4	13.3	7.4	20.9	5.1	19.8	5.8	<.001
LT (ms)	190	25.6	181	16.5	173	17.6	202	25.8	179	21.9	174	17.2	179	19.6	
MT (ms)	429	19.8	429	19.0	430	20.3	428	31.3	441	33.2	437	28.3	423	19.4	
*SD*LT (ms)	24.3	9.9	27.7	7.0	26.7	4.7	30.3	7.1	23.7	6.5	20.6	3.8	20.6	4.5	<.05
*SD*MT (ms)	26.0	8.3	30.0	7.0	27.4	4.5	31.2	7.5	25.0	5.6	21.9	4.5	21.6	3.8	<.01
GT (ms)	78.9	27.1	73.1	27.6	73.7	26.5	58.4	27.8	58.5	13.1	58.8	15.6	58.0	16.2	
D*x*W (mm)	326	48.8	295	49.9	276	57.5	330	110.5	372	90.8	388	94.4	356	73.8	<.01
D*x*E (mm)	318	48.9	299	33.4	298	51.1	315	72.1	347	57.8	362	65.0	342	47.9	<.01
D*x*S (mm)	37.0	27.4	15.7	22.2	13.2	31.5	36.3	36.9	49.9	38.4	63.6	45.2	51.9	39.8	<.01
PeakWv (m/s)	2.80	0.23	2.71	0.26	2.91	0.18	2.84	0.24	2.78	0.37	3.00	0.40	3.01	0.34	<.05

Note. CoG = control group; TrG = training group; CP = catching performance; LT = latency time; MT = movement time; *SD*MT and *SD*LT = intraparticipant variability of MT and intraparticipant variability of LT, respectively; GP = grasping time; D*x*W, D*x*E, and D*x*S = forward displacement of wrist, elbow, and shoulder, respectively; PeakWv = peak wrist velocity. The asterisks in the rightmost column of the table indicate significant interactions. *p* values indicate significant Test × Group interactions.

Profile of the Learning Process

To analyze the changes during the learning process within the TrG more thoroughly, we applied an ANOVA with repeated measures to the four test sessions (PrT, ImT, PoT, and ReT) for the 13.1-m/s trials of the TrG. The analysis revealed an effect of test session for CP, *SD*MT, D*x*W, D*x*E, and PeakWv (see Tables 1 and 2, respectively, for descriptions and statistical data). CP increased significantly from the PrT to the ImT, $p < .01$, and from the ImT to the PoT, $p < .05$ (see Figure 2). The individual progress in CP through the training program of all participants from the TrG and the mean performance curve are plotted in Figure 3.

In the ImT, *SD*MT did not differ significantly from that in the PrT but was significantly higher than that in the PoT, $p < .05$. Therefore, the decrease in *SD*MT after training, in comparison with that in initial catching, occurred in the second half of the learning process. The significant increases in forward displacement of wrist, $p < .05$, and elbow, $p < .01$, that were present after training (i.e., between PrT and PoT) mainly occurred in the first half of the learning process, as indicated by the strong tendency for increase in D*x*W and D*x*E in the ImT in comparison with those in the PrT, both *p*s = .065 for D*x*W and D*x*E. For *SD*MT, the changes in PeakWv because of the training program occurred in the second half of the learning process: PeakWvs in the ImT and PrT were identical, but PeakWv increased significantly from the ImT to the PoT, $p < .01$.

Transfer Effects

We determined the potential transfer effect to the other ball-speed conditions by conducting a 3 (ball-speed condition) × 3 (test session) × 2 (group) ANOVA with repeated measures on the first two factors.

The 3 × 3 × 2 analysis on CP revealed, in addition to the aforementioned Test × Group interaction, a strong tendency toward a Speed × Test × Group interaction (see Tables 3 and 4). That result indicated that the increase in CP of the TrG in comparison with that of the CoG that we had found for 13.1-m/s training speed was not equally strong for all ball-speed conditions. For *SD*MT, D*x*W, D*x*E, and D*x*S, the Test × Group interaction that was present at the training speed reappeared for the 3 × 3 × 2 analysis (see Table 4). However, we did not find an additional interaction of Test × Group with ball speed, indicating that transfer to the lower and higher ball-speed conditions occurred. For PeakWv, the Test × Group interaction did not arise in the 3 × 3 × 2 analysis. We also found a main speed effect for all kinematic variables (see Table 4): Whereas *SD*MT, D*x*W, D*x*E, and D*x*S decreased with increasing ball speed, PeakWv increased.

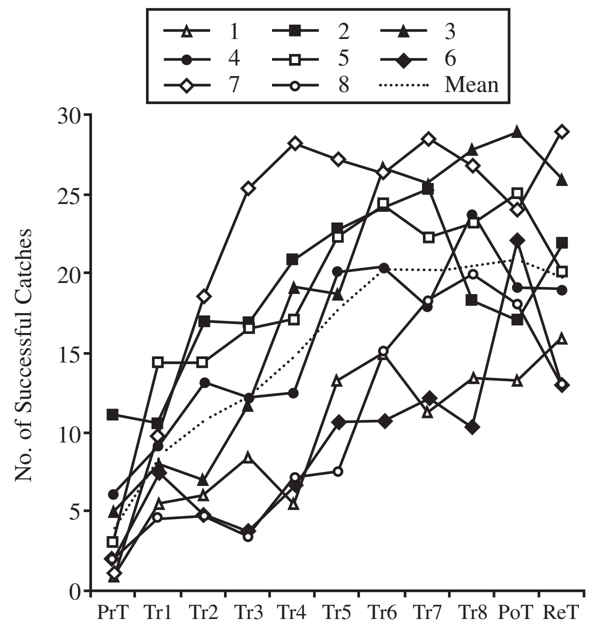

FIGURE 3. Participants 1–8 individual (thin lines) and mean (dotted line) performance curves across pretest (PrT), training sessions (Tr1–8), posttest (PoT), and retention test (ReT).

TABLE 2. Effect of Test Session for the Training Group and Post Hoc Comparisons Between Pretest and Intermediate Test (PrT–ImT), Intermediate and Posttest (ImT–PoT), Pretest and Posttest (PrT–PoT), and Posttest and Retention Test (PoT–ReT)

	Effect of test session			LSD post hoc comparisons (*p* values)			
Variable	$F(3, 21)$	p	η_p^2	PrT–ImT	ImT–PoT	PrT–PoT	PoT–ReT
CP	24.330	.000***	.777	.009**	.020*	.000***	.560
SD MT	8.107	.001**	.537	.114	.018*	.011*	.841
D*x*W	3.358	.038*	.324	.065(*)	.248	.031*	.093
D*x*E	3.927	.023*	.359	.065(*)	.140	.009**	.223
D*x*S	1.921	.157	.215	.294	.187	.078(*)	.249
PeakWv	3.896	.023*	.358	.580	.008**	.104	.987

Note. LSD = least significant difference. See Table 1 for other abbreviations.
*$p < .05$. **$p < .01$. ***$p < .001$. (*)nearly significant.

TABLE 3. Means and Standard Deviations for a Selection of Relevant Variables at the Pretest (PrT), Posttest (PoT), and Retention Test (ReT) for Control (CoG) and Training (TrG) Groups at the Three Ball Speeds

	CoG test session						TrG test session					
	PrT		PoT		ReT		PrT		PoT		ReT	
Speed	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
							CP (no. out of 30)					
L	8.6	4.7	10.9	4.7	12.7	6.6	10.9	5.3	20.6	4.9	19.5	10.3
M	4.0	3.2	5.0	3.4	6.1	4.4	3.9	3.4	20.9	5.1	19.8	5.8
H	1.9	1.8	1.8	2.4	2.2	2.3	1.5	1.9	11.3	7.3	10.3	6.1
							SD*MT (ms)*					
L	33.1	13.3	35.8	14.2	40.1	16.0	31.6	9.1	35.6	7.2	32.7	9.4
M	26.0	8.3	30.0	7.0	27.3	4.5	31.2	7.5	21.9	4.5	21.6	3.8
H	20.1	3.2	23.9	4.1	22.6	5.2	24.4	5.9	18.0	3.2	19.4	3.2
							*D*x*W (ms)*					
L	392	60.1	362	65.1	332.9	86.3	391	99.3	417	110.1	399	56.8
M	326	48.8	295	49.9	276.0	57.5	330	110.5	388	94.4	356	73.8
H	267	74.5	229	82.4	245.3	74.8	266	130.3	345	94.6	315	92.3
							*D*x*E (mm)*					
L	358	58.0	346	51.0	325	64.8	366	67.1	377	77.9	360	34.9
M	318	48.9	299	33.4	298	51.1	315	72.1	362	65.0	342	47.9
H	277	55.0	265	50.1	273	60.1	277	89.9	323	69.6	312	55.1
							*D*x*S (mm)*					
L	70	43.5	58	34.3	38	42.7	79	49.2	80	54.7	75	31.6
M	37	27.4	16	22.2	13	31.5	36	36.9	64	45.2	52	39.8
H	−5	35.4	−14	30.5	10	34.3	2	47.9	37	42.3	25	38.2
							PeakWv (m/s)					
L	2.46	0.15	2.42	0.16	2.52	0.19	2.67	0.35	2.75	0.52	2.70	0.44
M	2.80	0.23	2.71	0.26	2.91	0.18	2.84	0.24	3.00	0.40	3.01	0.34
H	3.19	0.31	3.01	0.18	3.29	0.25	3.35	0.17	3.24	0.43	3.28	0.37

Note. L, M, and H indicate low, medium, and high ball speeds. See Table 1 for other abbreviations.

TABLE 4. Statistical Results and Effect Sizes for the Test × Group Interaction, Main Speed Effect, and Test × Speed × Group Interaction Effect on the Set of Variables Reported in Table 3

	Test × Group			Speed			Test × Speed × Group		
Variable	$F(2, 30)$	p	η_p^2	$F(2, 30)$	p	η_p^2	$F(4, 60)$	p	η_p^2
CP	22.041	.000***	.595	78.963	.000***	.840	2.329	.066(*)	.134
*SD*MT	5.991	.006**	.285	26.731	.000***	.641	1.517	.209	.092
D*x*W	10.320	.000***	.408	59.999	.000***	.800	0.881	.481	.056
D*x*E	5.508	.009**	.269	55.555	.000***	.787	0.922	.457	.058
D*x*S	5.996	.006**	.286	75.042	.000***	.833	0.998	.416	.062
PeakWv	1.778	.186	.106	86.952	.000***	.853	0.792	.535	.050

Note. See Table 1 for abbreviations. η_p^2 = effect size.
$^{**}p < .01$. $^{***}p < .001$. (*)nearly significant.

Determining Factors in the Outcome of the Catch

We conducted a PCA with Varimax rotation (Brace, Kemp, & Snelgar, 2003) on all individual trials to examine what factors accounted for variability in the catching movement. For a total of 1,608 analyzed trials—519 successful catches and 1,089 misses—we first put 21 kinematic variables through a set of explorative PCAs. On the basis of the results of those preliminary PCAs, we identified and excluded redundant and trivial variables (communality < .7, and Kaiser–Meyer–Olkin measure [KMO] < .05 for separate variables) from the actual PCA. For all PCAs, we retrieved the KMO test and Bartlett's test of sphericity to check whether the PCA was an appropriate analysis for the used data set. We chose the number of components to extract on the basis of the Kaiser criterion (eigenvalue > 1.0). We also put the extracted components through a reliability analysis. We calculated the Cronbach alpha coefficient for each cluster of variables that was compounded in the separate components of the PCA.

From the preliminary PCAs, we found that the data set was appropriate for PCA analysis, KMO = .669; Bartlett's test of sphericity, p = .000. We identified 15 of the original set of 21 variables as trivial to the factor model—communalities < .7, KMO of the separate variable < .05, or both—and we excluded them from the proper PCA. Therefore, we conducted a final PCA with the remaining 6 variables. Again, the KMO test (KMO = .728; Bartlett's test, p = .000) evaluated PCA as justified for this restricted data set. We extracted two components that cumulatively explained 91% of total variance. The first component—C1_D*x*; eigenvalue = 3.149; 52.5% of the variance explained—contained three variables that were related to the place of interception: D*x*W, D*x*E, and D*x*S. The second component—C2_Hc; eigenvalue = 2.314; 38.6% of the variance explained—contained three variables that were related to the grasp: amount of hand closure during the grasp (Hc), mean hand-closing velocity (MeanHcV), and peak hand-closing velocity (PeakHcV). We assessed those two extracted components as reliable: We found Cronbach's alpha coefficients of .920 and .678, respectively, for C1_D*x* and C2_Hc. Analysis of the mean values of the extracted component scores (Figure 4) and the means of the separate variables that represented the extracted components (Table 5) suggested that successful catching is associated with a more forward point of interception and a larger and more dynamic grasp.

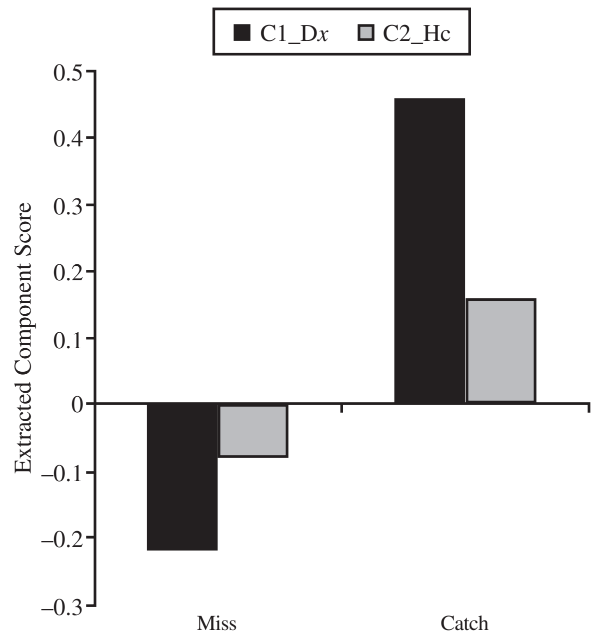

FIGURE 4. Mean factor scores for the both extracted components (C1_D*x* and C2_Hc) from the principal components analysis, according to movement outcome. C1 and C2 are the first and second components, respectively. D*x* and Hc, respectively, represent (a) wrist, shoulder, and hand forward displacement in the *x* direction and (b) hand closure.

TABLE 5. Factor Loadings (Rotated Solution) of the Kinematic Variables on the Two Components Extracted by the Principal Components Analysis for Missed and Successful Catches Over All Groups, Speed Conditions, and Test Sessions

	Extracted components		Miss		Catch	
Kinematic variable	C1_D*x*	C2_Hc	*M*	*SD*	*M*	*SD*
D*x*W (mm)	**.963**	.085	308.0	103.4	376.4	82.9
D*x*E (mm)	**.963**	.095	308.1	69.8	352.9	56.9
D*x*S (mm)	**.964**	.037	25.4	49.0	58.1	44.0
MeanHcV (mm/s)	.078	**.973**	197.9	157.0	244.9	156.7
PeakHcV (mm/s)	.099	**.951**	407.1	326.7	510.4	341.2
Hc (mm)	.037	**.890**	15.7	16.7	18.4	15.6

Note. The variables that loaded on the respective components are shown in bold. C1 and C2 = first and second principal components, respectively. HcV = hand-closing velocity. For other abbreviations, see Table 1.

Discussion

In the present experiment, our main aim was to study changes in performance and kinematics during the acquisition of a one-handed catch. In line with our expectations, the intensive training program consisting of 1,440 trials yielded a substantial increase in CP. Because we assumed that participants had mastered a basic catching movement before the start of the experiment, we did not expect radical changes in the coordination pattern of the catch. Yet, we hypothesized that an increase in performance outcome would involve some clear kinematic changes. We found a few discrete changes: Increased temporal consistency, shift in spatial location of the ball–hand contact point away from the catchers' frontal plane, and higher peak velocity of the transport of the hand toward the ball accompanied the gain in CP. A first possible explanation for those sparse kinematic results lies in the stage of learning of the participants. It is likely that participants had already mastered a basic coordination pattern for catching before entering the training program. Therefore, a fine attunement of the movement, involving only subtle adaptations, emerged. Because of stringent spatial and temporal constraints in ball catching, a minor change in kinematics could be sufficient to fulfill the spatial and temporal requirements, leading to an increase in catching performance. A second possible explanation for those sparse kinematic results lies in interparticipant variability in executing a catch and differences in learning pace. Because skill acquisition is an individual process, participants in the present study were initially located at varying places along the learning trajectory. Hence, adaptations that took place in one participant may not yet have occurred in another. Therefore, those refined adaptations may have been concealed from statistical analysis. Moreover, intraparticipant variability may have played an additional role in the absence of more pronounced kinematic changes because the same catcher's various motor answers could fit the spatiotemporal requirements of the task.

Learning Effect and Associated Kinematic Changes

The catching performance results indicated that the extensive training program resulted in a permanent gain in catching performance for the TrG. Although the CoG did not show any improvement, CP of the TrG increased 500% and persisted after 10 weeks, indicating an evolution from poor to subexpert catcher. We did not find changes in the temporal structure of the catch: LT, MT, and GT remained the same over all test sessions for both groups. Therefore, grasping error (i.e., starting the final closure of the hand too late) did not seem to be responsible for the weak performance at the PrT.

The changes in kinematics that we found are not new to the field of motor learning and control (although researchers established some of them from a different perspective), and they were situated at three different levels. First, we observed an increase in consistency of the temporal structure of the catch. That type of decrease in within-participant variability is peculiar to learning, especially in closed skills (i.e., skills performed in a relatively stable and predictable environment) such as the one in this experiment: As the participant acquires a skill, its execution becomes more consistent (Button, MacLeod, Sanders, & Coleman, 2003; Darling & Cooke, 1987; Guarrera-Bowlby & Gentile, 2004; Lee, Swinnen, & Verschueren, 1995; Wollstein & Abernethy, 1988). In addition to the increased temporal consistency, participants established spatial and temporal adaptations. At the spatial level, both groups even showed changes in opposite directions. At the posttest, we found an increase in D*x*W, D*x*E, and D*x*S for the TrG, whereas we found a retreat of the catching arm for the CoG. A novice catcher might perceive the temporal constraint of the task in the present study to be hardly feasible. Therefore, the retreat of the interception point in the untrained group may be an adaptation mechanism that enables them to deal with the imposed temporal constraint of the new task properties. Investigators have repeatedly described such an adaptation mechanism as a result of increasing ball velocity in ball catching (Laurent, Montagne, & Savelsbergh, 1994; Mazyn et al., 2006). In addition, with only 30 trials in each ball-speed condition for every test session, habituation to the task may not have emerged because possible practice habituation effects that would have occurred during those test trials would have faded by the time of the next test session. In contrast, the TrG caught the ball farther in front of the shoulder after training in comparison with their initial catching behavior. Shifting the interception point more forward could have resulted in better catching performance in several ways. First, the catching hand was positioned more in the central-vision field, which may be beneficial for performance of nonexperts, as suggested in earlier studies (Fischman & Schneider, 1985; Savelsbergh & Whiting, 1988; Smyth & Marriott, 1982). A second aspect that may facilitate catching performance lies in the more comfortable catching-arm configuration that originates when people catch the ball more distantly (see Mazyn et al., 2006). Gray and Sieffert (2005) also designated such a strategy of moving the hand toward the ball in catching as "a more advanced strategy that is used by more experienced players" (p. 1020). An alternative explanation is that catchers become more efficient and accurate in using visual information from the flight path, which allows them to intercept the ball earlier in flight and leaves room for them to retract the hand and correct its position in case of unexpected changes in or misperceptions of the ball flight. Last, PeakWv increased because of practice within the TrG. Bringing the hand faster to the interception point leaves catchers more time to adjust and enhances their fine-tuning of the catch (Jeannerod, 1988; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987).

Profile of the Learning Process

Mean CP increased gradually across the practice sessions and leveled off just before the end of the training program.

At first glance, that pattern looks like a textbook example, but it is obvious from Figure 3 that researchers must use care when interpreting the mean performance curve. In reality, we found a large variety of progression patterns. That observation indicates that learning is an individual matter and cannot be generalized: Just as there is no average person, there is no average learning pattern. At first sight, the spectrum of individual performance curves may explain the detection of only scant changes at the kinematic level. As we have argued, however, the temporal and spatial constraints of the catching task entail that a minor adjustment in just one kinematic variable can result in significant improvement in catching performance. This finding could explain how those few subtle adaptations still engender a relatively large gain in performance outcome. As we mentioned, our participants already possessed the basic coordination pattern, which was confirmed by the absence of changes in coordination variables (for cross-correlation measures, see Mazyn et al., 2006) observed in this study. Therefore, participants obtained a substantial gain in CP through refined tuning of the catch to its demanding spatiotemporal requirements.

Moreover, we found that participants acquired spatial and temporal changes at different time scales: Participants implemented displacement of the interception point (spatial adaptation) before adjustment in wrist velocity (temporal adjustment). During the first half of the training program, we observed mainly spatial changes. After becoming familiar with the new temporal task constraint, participants reached their hand more forward to catch the ball. Only in the course of the second week of practice did PeakWv increase, and hence participants transported the hand faster to the place of interception. The observation that spatial changes in the kinematics of the catch precede temporal changes during practice is in line with reports in the existing literature (Alderson, 1974; Magill, 2004; Marteniuk & Romanow, 1983). In addition, closer analysis of the data showed that *SD*MT also reduced only during the second half of the training program. That finding is congruent with the general law in motor learning that movement consistency appears only at the later stages of skill acquisition (Gentile, 2000).

Transfer Effects

The Test × Group interaction over all ball-speed conditions is clearly visible in Figure 2. Participants attained an improvement in CP not only at the training speed but also at the higher and lower ball-speed conditions. Experience from the test sessions did not result in an increase in performance for the CoG in the 13.1- and 15.5-m/s conditions. However, the CoG did show a slight progression at the slowest ball speed. Because catching a ball that approaches at 10.8 m/s is relatively easy, a fast performance gain already arose within those few test sessions in this study. Note that CP already increased from the screening test (about 15% successful catches) to the PrT (about 30% successful catches) for both groups. Still, the improvement in performance from PrT to ReT for the TrG (29% successful catches) was twice the progression for the CoG (13.7% successful catches).

For the changes in temporal consistency (*SD*MT) and spatial variables (D*x*W, D*x*E, and D*x*S), we found a transfer effect from the training speed to both the slower and faster ball-speed conditions: Participants also appealed to the forward shift of the interception point and more consistent movement time that emerged with training when catching balls at diverging speeds. That finding indicates not only that acquiring a skill under specific temporal constraints benefited participants' performance of that skill in a new context but also that participants reproduced the kinematic strategy that they had acquired to achieve the original movement goal (catching a ball at 13.1 m/s). However, we did not find increased PeakWv for the TrG in the PoT for the lower and higher ball speeds. The spatial strategies are apparently more easily transferred to new situations than are the temporal ones. The different time scales in learning between participants may explain that finding: Because spatial adaptations emerged earlier in the acquisition process, stable spatial attunements were already manifested within the catching movements of all participants, and hence participants more easily adopted them under varying temporal constraints. On the contrary, catchers will vary in the extent to which they acquire the precise temporal tuning, so that in some catchers in this study, that kind of adjustment did not yet transfer toward different task properties.

In this study, we varied only the temporal aspects of the ball flight in the transfer tests. Although there was some degree of spatial variability in ball trajectories during acquisition and testing, we could have drawn more generalizable conclusions concerning the acquisition of catching if we had also included spatial aspects (i.e., different ball trajectories). More specifically, we could have corroborated or refuted the finding that spatial changes in kinematics seem to precede temporal changes during the acquisition as a general learning principle by introducing temporal variations as well as spatial variations in ball flight during acquisition and testing.

Our results revealed several subtle adaptations by participants that could explain the gain in performance that the extensive training program induced. We found that a shift in interception location with changes in movement dynamics was a crucial element in the fine-tuning stage of acquisition of catching. In determining the kinematic factors of importance in the outcome of the catching movement, the PCA established that performers realized successful catching by using a more distant interception point and closing the hand more actively. In earlier work on catching and grasping, investigators have frequently distinguished between two functional units: a transport component and a manipulation phase (Alderson, Sully, & Sully, 1974; Jeannerod, 1984; Wallace & Weeks, 1988). The extracted components from the PCA substantiated the relative independence of those two phases. Notwithstanding the fact that the kinematic analysis of the catching movement revealed that participants made only few adjustments in the transportation of the hand to the future interception point, the results from the PCA validated the distinction between the transportation phase and the manipulation phase in ball catching.

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NOTE

1. We derived the moment of ball–hand contact from the 3D visual reconstruction of the catching movement in the Qualisys software program. The impact of the ball on the hand was clearly visible as a sudden, backward jerky movement of the metacarpal and finger markers. Therefore, for the complete misses, we were unable to determine ball–hand contact. Thus, we included only successful catches and touches in the kinematic analysis.

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