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Adaptation to Separate Kinematic and Dynamic Transformations in Children and Adults

Petra Jansen-Osmann, Stefanie Richter, Thomas Schinauer, Petra Fuchs, and Karl-Theodor Kalveram

The question addressed in the present study is whether children and adults are able to combine and decompose separate kinematic (visual-feedback-shift) and dynamic (velocity-dependent force) transformations in goal-directed arm movements. A total of 64 participants (32 adults and 32 children) performed horizontal forearm movements using a single-joint arm manipulandum. When participants first learned kinematic and dynamic transformations separately, target error decreased in a subsequent combined transformation task. This effect was based on previous learning of the kinematic transformation. When they first learned the combined transformation, target error was smaller in the following kinematic—but not in the dynamic—transformation. No difference was found in adaptation performance between children and adults. The results suggest that there are two separate models for the kinematic and dynamic transformation and that a possible differentiation of kinematic and dynamic features of the motor task might already be present at age 11.

Key Words: motor learning, motor control, internal motor models, humans, children

To accurately reach a target in the environment, an appropriate series of elbow angles first must be computed from visual information about the target localization (inverse kinematic transformation; e.g., Kalveram, 1991). Next, the limb is brought to its desired goal according to the planned joint trajectory by means of force or muscle activation (inverse dynamic transformation; Atkeson, 1989; Kalveram, 1992; Wolpert & Kawato, 1998).

Inverse kinematic and dynamic transformations can be manipulated to investigate adaptation processes. Results of a study by Flanagan and colleagues support the notion that learning novel kinematic versus dynamic environments is independent and relies on separate sensory systems (visual and proprioceptive) of

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Jansen-Osmann, Schinauer, Fuchs, and Kalveram are with the Dept of Psychology, Heinrich-Heine-University of Düsseldorf, Germany. Richter is with the German Aerospace Center, Institute for Aerospace Medicine, Cologne, Germany.

the central nervous system (CNS) (Flanagan, Nakano, Imamizu, Osu, Yoshioka, & Kawato, 1999). The authors investigated two-dimensional pointing movements with transformations on the limb's visual feedback (feedback rotation) or force condition (application of viscous rotary field). They showed that learning the kinematic and dynamic transformations separately beforehand proves advantageous when participants have to cope with a combined kinematic and dynamic transformation (composition hypothesis). They assumed that the CNS can effectively combine internal models of two transformations, which were learned immediately before. When participants had to perform movements under both the dynamic and kinematic transformation, their pointing error decreased if the immediately following condition involved altered kinematics, but not dynamics (decomposition hypothesis). That is, a decomposition effect was found for the kinematic transformation only.

Based on the study by Flanagan and colleagues, our main goal was to investigate motor performance under kinematic and dynamic changes in children. It is known that infants begin to engage in goal-directed reaching and grasping at the age of about 4 to 5 months (Hofsten, 1991; Konczak, Borutta, Topka, & Dichgans, 1995) but cannot perform adult-like kinematics until they have reached the age of two years (Konczak, Borutta, & Dichgans, 1997). Furthermore, our own data demonstrate that children as young as four years of age were able to compensate for novel dynamics (Konczak, Jansen-Osmann, & Kalveram, 2003), and even 6-year-old children showed so-called transferred after-effects (Shadmehr & Mussa-Ivaldi, 1994). After the removal of an applied force, the trajectories revealed an overshoot in the opposite direction of that when first introducing the force. These after-effects were also found in untrained portions of the workspace (transferred after-effects), which argues in favor of generally stable internal models. It is noteworthy, however, that these young children were unable to adapt to the novel dynamics at the same rate as children in late childhood or as adults (Jansen-Osmann, Richter, Konczak, & Kalveram, 2002).

In contrast to adaptive behavior in novel dynamics, we found that 9-year-old children had lower endpoint accuracy than adults if visual feedback was absent during the reaching movement. Thus, it seems that visual information about movement geometrics provides a crucial bit of information to younger children, which, when missing, yields slower and less accurate movements (Jansen-Osmann, Beirle, Richter, Konczak, & Kalveram, 2002). Similarly, Ferrel, Bard, and Fleury (2001) investigated pointing movements under disturbed visual feedback in children and adults. They demonstrated that while children at age 11 showed similar endpoint accuracy as adults, they had not yet reached adult level regarding the adaptive process of converting shifted visual information into smooth trajectories.

The present study was conducted using an approach similar to that of Flanagan et al. (1999), who investigated two-joint movements. There is evidence that the information relevant to the motor system in two-dimensional movements is represented in a vector format, which comprises two computations (e.g., Gordon, Ghilardi, & Ghez, 1994; Krakauer, Pine, Ghilardi, & Ghez, 2000). First, a scaling factor specifying movement amplitude (learned from errors in extent) and second, a reference axis determining movement direction (learned from errors in direction) (Krakauer, Ghilardi, & Ghez, 1999; Pine, Krakauer, Gordon, & Ghez, 1996). Unlike their work, we investigated one-joint-movements, which means that the kinematic transformation solely required the learning of a new scaling factor from errors in extent. Though learning of a new reference axis was not required and thus the kinematic transformation can be considered comparably simple, preceding experiments revealed that the task was not too easy for children in the age range investigated here. As a dynamic transformation we chose the application of a velocity-dependent viscous force. In contrast to the study of Flanagan et al. (1999) the participants in our study did not have any visual feedback of their moving arm to correct their movement during execution.

Several questions were addressed in the present study. First, do participants adapt faster to a combined transformation when performing the separate transformations beforehand (composition analysis)? Second, do participants adapt faster to the separate transformations when performing the combined transformation beforehand (decomposition analysis)? Third, are there differences in the adaptation process to a kinematic versus dynamic transformation? Finally, are there developmental differences between children and adults concerning adaptation to the two transformations and the composition and decomposition analysis?

Method

Participants

Thirty-two adults (22 women, 10 men) and 32 children (16 girls, 16 boys) participated in the study. All were right-handed except for two adults (both women) and one child (a girl). The adults ranged in age from 21–45 years (mean age: 27.34 years ± 6.02 years); the childrens' ages ranged from 10–12 years (mean age: 10.91 ± 0.64 years). All adults as well as all parents of the children gave written informed consent to take part in the experimental procedure. The experiment took about 20 min for each individual to complete.

Apparatus

Participants sat in an adjustable chair, facing a concave projection screen about 1.5 m in front of them. Their right forearm was inserted into a brace attached to the lever of a robot manipulandum. It allowed only flexion–extension movements in the horizontal plane. The size of the brace was adjusted to each participant's arm anthropometrics to ensure a secure and tight fit. Participants viewed two illuminated arrows on the projection screen. A "goal arrow" indicated the required target position; a "hand arrow" specified the actual angular position of the forearm (90° elbow angle = 0° on the screen, right to the mid-sagittal). This "hand arrow" was shown on the projection screen through coupling of a pointer to the position of the lever of the robot manipulandum. The apparatus is illustrated in Figure 1.

Procedure

Pointing Movements. Prior to each trial, the participant actively aligned the hand arrow to the position of the goal arrow at 0°. The goal arrow then moved to a position of 20° or 40° on the screen, depending on the particular experimental condition.

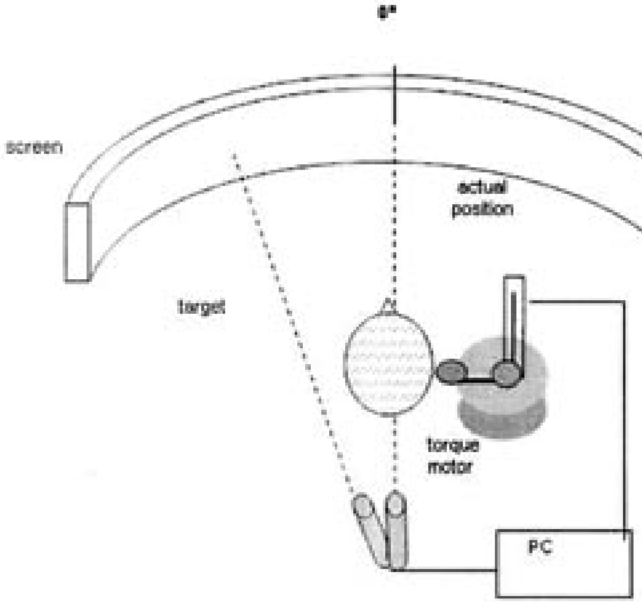

Figure 1—Experimental setup. Participants viewed two illuminated arrows on a screen in front of them. The top arrow indicated the goal, the bottom arrow the feedback of the actual arm position. Participants were asked to match both arrows by performing a flexion movement of their forearm. A torque motor was mounted underneath the elbow joint axis exerting a damping force in specific trials (dynamic and combined transformation). In the kinematic and combined transformation a visual feedback-shift—displaying the doubled joint angle—was applied.

The adults and children were instructed to perform a goal-directed forearm flexion movement to the respective target position (see Figure 1). The participants were told to move accurately and at a quick pace; they could not see their hand during the movement. Furthermore, the hand arrow disappeared with movement onset and appeared again after the transport phase had ended. The transport phase of the reach ended after the first acceleration and deceleration phase. It is thus the latest point in the trajectory where we can reasonably assume that the observed kinematics were the result of feedforward control and were not entirely influenced by the processing of afferent feedback (Konczak et al., 2003). All participants were able to correct their movements when the hand arrow reappeared. We were not interested in these corrective movements, however. Maximum time allowed per trial was 3 s. In other words, the target arrow jumped from the starting position to the target position and back every 3 s. Reacting as quickly as possible was not emphasized in the instruction, as it is not crucial to the question of movement execution, and thus reaction time was not analyzed.

Dynamic Transformation. During specific blocks of trials the torque motor generated a force with the amplitude being proportional to the angular velocity of the participant's arm movement. The damping coefficient was 1 Nm/rad/s, which generated a velocity-dependent force that *opposed* forearm motion ("viscous damping"). Participants experienced positive damping as if they were moving their arm in a glutinous fluid.

Kinematic Transformation. In the kinematic transformation, the hand arrow indicating arm position was shifted to the left by a factor of 2. For example, when arm position was actually 10°, the hand arrow was fed back at a position of 20° on the screen. Otherwise stated, a gain of 2 yielded a displayed feedback angle of double extent, i.e., a target of 40° was reached with a movement of 20°.

Changes in the dynamic or kinematic conditions were perceivable only after the onset of each new trial. The torque motor received its input from a workstation computer. Control software to drive the torque motor was developed based on MATLAB/SIMULINK technical computing language.

Experimental Design. The experimental design is illustrated in Table 1. Four experimental blocks were administered consisting of 40 trials each and leading to a total of 160 trials per participant. Participants were not allowed to take a break between blocks. We applied blocks with a damping force (= dynamic transformation), with a shift in visual feedback (= kinematic transformation) as well as with both damping force *and* a shift in visual feedback (= combined transformation).

The participants were randomly assigned to four subgroups. All participants first completed 40 trials in the baseline condition (B) without kinematic and dynamic transformation. This condition was included to familiarize the participants with the manipulandum and to obtain a reference measure of performance. Two groups of participants then completed 40 trials in the combined transformation (C, kinematic and dynamic) followed by 40 trials in the kinematic (K) and dynamic (D) transformation each, counterbalanced across participants (group B-C-K-D and B-C-D-K). Two additional groups of participants each completed 40 trials in the kinematic and dynamic transformation counterbalanced across participants, followed by 40 trials in the combined transformation (group B-K-D-C and B-D-K-C).

Table 1 Experimental Design

	Decomposition		**Composition**	
	Group "BCKD"	**Group "BCDK"**	**Group "BKDC"**	**Group "BDKC"**
Block 1	Baseline			
Block 2	Dynamic and Kinematic		Kinematic	Dynamic
Block 3	Kinematic	Dynamic	Dynamic	Kinematic
Block 4	Dynamic	Kinematic	Dynamic and Kinematic	

Measurements

Data Analysis. Angular velocity was measured by a tachometer and angular position by a high-precision potentiometer, both connected to the motor shaft. Velocity and position were recorded for each trial. The data were sampled at 500 Hz and digitized with a 12-bit A/D converter (model ME-300, Meilhaus Electronic GmbH, Puchheim, Germany). Digital data were stored on hard drive. Positional data were low-pass filtered offline with a second-order Butterworth filter with a cut-off frequency of 10 Hz. To accomplish comparability between the trajectories, the curves were aligned at movement onset. Movement onset was defined as the time when the angular path differed more than 5° from the starting position.

Positional Error Score. For each trial, we determined the angular position reached after the first acceleration and deceleration phase, i.e., the time when the acceleration curve passed the x-axis for the second time. After this first acceleration and deceleration phase, the transport phase of the reach had ended. The value of the attained angular position was subtracted from the required target position and the absolute value was computed. Absolute target error was used because our main interest was the accuracy with which the target was reached (Magill, 1993). There is an inherent directionality to the kinematic and dynamic transformation, however. The kinematic transformation requires a scaling down of movement amplitude, i.e., it leads to target overshoot if adaptation is inadequate, while the dynamic transformation leads to target undershoot. This bias was investigated in a comparison analysis (see below) with the help of the constant error (Magill, 1993).

Statistical Analysis

Baseline Performance. We computed the mean absolute target error for the last 20 trials in the first block. We then compared the performance between the four experimental groups and the two age groups by means of a univariate ANOVA.

Composition Hypothesis. If participants benefited from learning separate transformations when asked to perform movements under a combined transformation, decay of absolute target error should be steeper in the combined transformation with prior learning of the separate transformations than in the combined transformation without prior learning of the separate transformations. Thus we compared target error in the combined transformation in the second block of the experiment, (groups B-*C*-K-D and B-*C*-D-K) with the performance in the combined transformation with prior learning of the separate transformations in the fourth block of the experiment (groups B-K-D-*C* and B-D-K-*C*). To evaluate performance, a repeated ANOVA was performed to examine effects of age, condition, and trial-by-trial evolution to investigate learning (trial). In all analyses Greenhouse-Geisser corrections of degrees of freedom were applied where necessary.

The groups with and without prior learning of the separate transformations differed with respect to the number of movements performed before the combined transformation. Thus, to ensure that potential effects were not only the result of practicing forearm movements per se, we performed a control analysis. We first calculated the mean absolute target error in each trial of the second and fourth block across all four experimental groups and both age groups (i.e., B*C*KD, B*C*DK, B*K*DC, B*D*KC and BCK*D*, BCD*K*, BKD*C*, and BDK*C*). Mean target error in the second and fourth block across all experimental groups was taken as reference as it is assumed to represent the "block effect," i.e., the target accuracy which is caused by the block number irrespective of condition. Age groups were merged for the calculation of these reference values as no effects of age were found in the main analysis (see below). Secondly, we calculated an ANOVA (mean target error of all four experimental group versus mean target error of the two groups with the combined condition) and age as between-participants factors and trial and condition (with prior learning of the separate transformations versus without prior learning of the separate transformations) as within-participant factor. If the composition effect was not the result of movement practicing per se, the mean error in the combined conditions should reveal a larger reduction from the second to the fourth block than the overall mean target error across all four experimental groups.

To further investigate if potential composition effects are based on the immediately preceding learning of the kinematic or dynamic transformation, we compared performance in the combined transformation without prior learning (groups B-*C*-K-D and B-*C*-D-K) with (a) the performance in the combined transformation with prior dynamic (B-K-D-*C*) and (b) the performance in the combined transformation with prior kinematic learning (B-D-K-*C*).

Decomposition Hypothesis. If participants benefited from a combined transformation when asked to perform movements under separate transformations, decay of absolute target error should be steeper in the condition with prior learning than in the condition without prior learning of the combined transformation. For both separate transformations, we compared performance in the second block in the groups without prior learning of the combined transformation (B-*K*-D-C and B-*D*-K-C) with performance in the third block of the groups with prior learning of the combined transformation (B-C-*K*-D and B-C-*D*-K). A repeated ANOVA was performed to examine effects of age, condition and trial.

To ensure that potential decomposition effects are not only caused by the practicing of forearm movements per se, we compared the performance in the kinematic and dynamic transformation within the third block between group B-C-*K*-D and B-D-*K*-C and between groups B-C-*D*-K and B-K-*D*-C in post hoc analyses. In this third block, participants had performed the same number of trials, but differed with respect to the kind of transformation experienced before. Half the participants had performed the combined transformation, while the other half had performed the opposite separate transformation (repeated ANOVA: age, condition and trial).

Comparison of Dynamic and Kinematic Transformation. To compare adaptation in the dynamic and kinematic transformation, we evaluated learning in these conditions in the second block of groups B-*K*-D-C and B-*D*-K-C by means of a repeated ANOVA (age × condition × trial). In the comparison analysis both the absolute and constant error were used as dependent variables to assess both target accuracy and error bias.

Analysis of Learning Effects. For each experiment we considered Trials 2 through 6. We excluded the first trials, because we know from previous experiments that the first trial of each block reflects aftereffects only. We were primarily interested in differences in learning between blocks but not in aftereffects. We disregarded trials beyond the sixth trial, because we know from previous experiments that even younger children are able to adapt to changed dynamics within four to five trials after transition (Jansen-Osmann et al., 2002; Richter, Jansen-Osmann, Konczak, & Kalveram, 2003). Similarly, in the present study, the effect of condition did not persist after six trials, because the target error was equal to the mean baseline error from the seventh trial on. One exception was the kinematic transformation in the decomposition experiment.

Results

Baseline Performance

All participants regardless of their age and experimental group seemed to be comparable with respect to "unperturbed" movements. That is, neither the comparison between adults and children [$F(1, 55) = 3.31, p = .123$; $\text{mean}_{\text{adults}}$: 2.53° ($SE = 0.21°$), $\text{mean}_{\text{children}}$: 2.99° ($SE = 0.21°$)], nor between the four experimental groups [$F(3, 55) = 0.61, p = .609$; $\text{mean}_{B\text{CKD}}$: 2.82° ($SE = 0.29°$), $\text{mean}_{B\text{CDK}}$: 2.28° ($SE = 0.29°$), $\text{mean}_{B\text{KDC}}$: 2.97° ($SE = 0.29°$), $\text{mean}_{B\text{DKC}}$: 2.43° ($SE = 0.30°$)] revealed significant differences in the mean absolute target error in the baseline condition [interaction between age and condition $\text{F}(3, 55) = 0.64, p = .590$].

Composition Hypothesis

Composition Analysis. Figure 2 reveals that absolute target error was on the average slightly higher in the groups without prior learning of the separate transformations (block 2 in the groups B-*C*-K-D and B-*C*-D-K) than in the groups with prior learning of the separate transformation (block 4 in the groups B-K-D-*C* and B-D-K-*C*; significant effect of condition: [$F(1, 60) = 11.807, p = .001$]. Adaptation differed in the condition with prior learning of the separate transformations than in the condition without prior learning of the separate transformations (significant interaction between trial and condition: [$F(3, 187) = 3.867, p = .009$]. More specifically, while target error was initially small in the condition with prior learning, post hoc paired comparisons revealed that in the condition without prior learning, mean target error in the second trial was larger than mean target error in each subsequent trial ($p \leq .002$), in which target error was constant ($p > .26$). That is, adaptation took place rather quickly. There was a significant effect of trial [$F(3, 187) = 9.176$, $p < .0001$], but neither the age effect nor other interactions reached significance (all p values > .14). The means and standard errors of the composition analysis for the children compared to the adults are given in Table 2.

Post Hoc Analyses. First, analyzing possible practicing effects we found a significant effect of trial [$F(3, 187) = 32.794, p < .0001$] and condition [$F(1, 60) = 26.818$, $p < .0001$] and a significant interaction between these two factors [$F(3, 187) = 8.463$, $p < .0001$] as in the main analysis. Furthermore, mean target error decreased more strongly from the second to the fourth block in the two groups with the combined condition than in all four groups. In the second block, the mean target error did

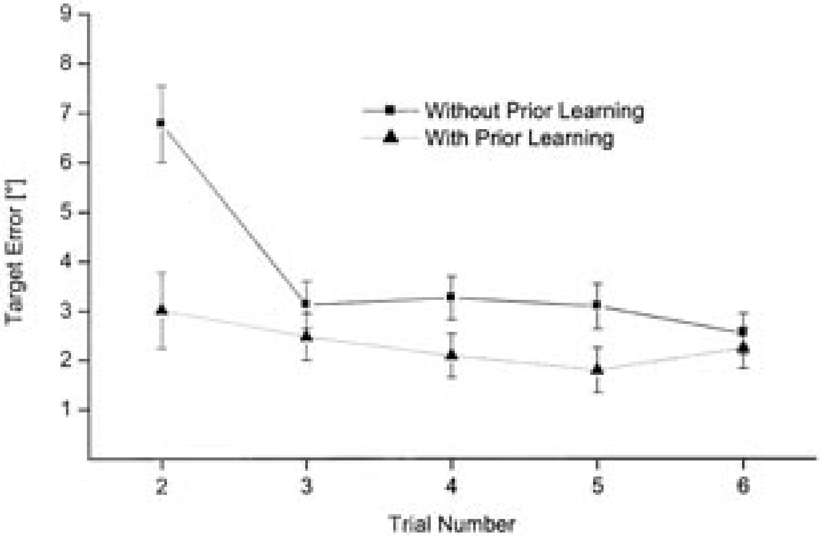

Figure 2—Composition hypothesis. Mean values and standard errors of the absolute target error in Trials 2–6 averaged across age groups for participants without and with prior learning of the separate transformations.

Table 2 Means (Standard Errors) in the Two Age Groups in the Main Analyses for the Five Trials (Trial 2 -6) Analyzed in Each Condition

	Children	Adults
Composition		
With prior learning	3.0 (0.5), 3.1 (0.9), 2.5 (0.5), 1.6 (0.2), 2.4 (0.4)	3.0 (0.8), 1.6 (0.4), 1.0 (0.2), 2.0 (0.6), 2.1 (0.6)
Without prior learning	6.4 (1.6), 3.1 (0.6), 4.5 (1.1), 3.9 (1.0), 3.1 (0.9)	7.2 (1.2), 3.2 (0.6), 2.0 (0.4), 2.3 (0.6), 2.0 (0.3)
Decomposition		
Kinematic		
With prior learning	1.8 (0.3), 1.6 (0.5), 2.3 (0.4), 1.8 (0.4), 1.9 (0.7)	1.8 (0.5), 2.5 (0.4), 1.9 (0.3), 1.3 (0.5), 1.9 (0.6)
Without prior learning	9.0 (1.6), 5.0 (1.7), 5.6 (1.5), 4.5 (1.6), 4.1 (1.5)	6.5 (1.1), 4.4 (1.1), 2.4 (0.5), 3.6 (1.0), 3.5 (1.1)
Dynamic		
With prior learning	4.4 (0.7), 5.1 (0.7), 3.5 (0.7), 2.6 (0.5), 2.6 (0.3)	7.3 (0.5), 4.9 (0.4), 4.7 (2.0), 3.0 (0.5), 2.2 (0.4)
Without prior learning	1.4 (0.3), 3.3 (0.8), 3.4 (1.0), 2.9 (0.9), 2.3 (0.5)	2.5 (0.3), 2.8 (0.6), 1.6 (0.3), 2.7 (0.4), 2.5 (0.4)

not differ between the two combined groups [mean: 3.76° (*SE* = 0.37)] and all four groups [mean: 3.73° (*SE* = 0.0)]. In contrast, in the fourth block, mean target error was smaller in the two combined groups [mean: 2.32° (*SE* = 0.20)] than in all four groups [mean: 3.00° (*SE* = 0.00)]. Unfortunately, this interaction between condition and practice failed to reach significance [$F(1, 187) = 2.868$, $p < .1$]. There were no other significant effects and interactions, respectively (all p values > .14).

Second, we found that when the dynamic transformation preceded the combined condition, the target error declined from Trials 2 through 6 in both conditions and was higher in the condition without prior learning (average across the groups B-*C*-K-D and B-*C*-D-K) than in the group with prior learning [B-K-D-*C*; significant main effects of trial: $F(3, 125) = 7.676$, $p < .0001$ and condition: $F(1, 44) = 4.343$, $p = .043$]. All other effects were nonsignificant (all p values > .23). When the kinematic transformation preceded the combined condition, the target error was higher in the condition without prior learning (average across the groups B-*C*-K-D and B-*C*-D-K) than in the group with prior learning (B-D-K-*C*) and declined from Trials 2 through 6 in this condition only [trial: $F(3, 134) = 3.656$, $p = .014$; condition: $F(1, 44) = 9.602$, $p = .003$; trial × condition: $F(3, 134) = 3.885$, $p = .01$]. All other effects were nonsignificant (all p values > .11).

In summary, it was shown that there was a composition benefit which was the result of learning the separate kinematic transformation immediately beforehand. This benefit did not seem to be caused by practicing forearm movements per se.

Decomposition Hypothesis

Decomposition Analysis. With respect to kinematic transformation, the top panel of Figure 3 shows that the target error was higher in the condition without prior learning of the combined transformation (B-*K*-D-C) than in the condition with prior learning of the combined transformation (B-C-*K*-D). It significantly declined from Trial 2 to 3 ($p \leq .002$), and remained constant thereafter ($p > .21$). It did not reach baseline level within six trials, however. There were two main effects for the factors trial [$F(3, 91) = 5.36$, $p = .001$] and condition [$F(1, 28) = 15.112$, $p = .001$] and a significant interaction between these two factors [$F(3, 91) = 6.143$, $p = .001$]. There were no other significant effects (all p values > .12).

As regards dynamic transformation, the bottom panel of Figure 3 shows that the target error was higher in the condition with prior learning of the combined transformation (B-C-*D*-K) than in the condition without prior learning of the combined condition (B-*D*-K-C) and only declined from Trials 2 through 6 in this condition. Accordingly, there were two main effects for the factors trial [$F(2, 58) = 4.213$, $p < .05$] and condition [$F(2, 58) = 14.759$, $p < .0001$] and an interaction between these factors [$F(2, 58) = 5.667$, $p < .01$]. All other effects were nonsignificant (all p values > .1).

The means and standard errors of the decomposition analysis for the children compared to the adults are given in Table 2.

Post Hoc Analysis. Post hoc analysis for practice effects in the kinematic decomposition effect revealed that the target error was higher in the kinematic transformation with prior learning of the opposite transformation (B-D-*K*-C) than

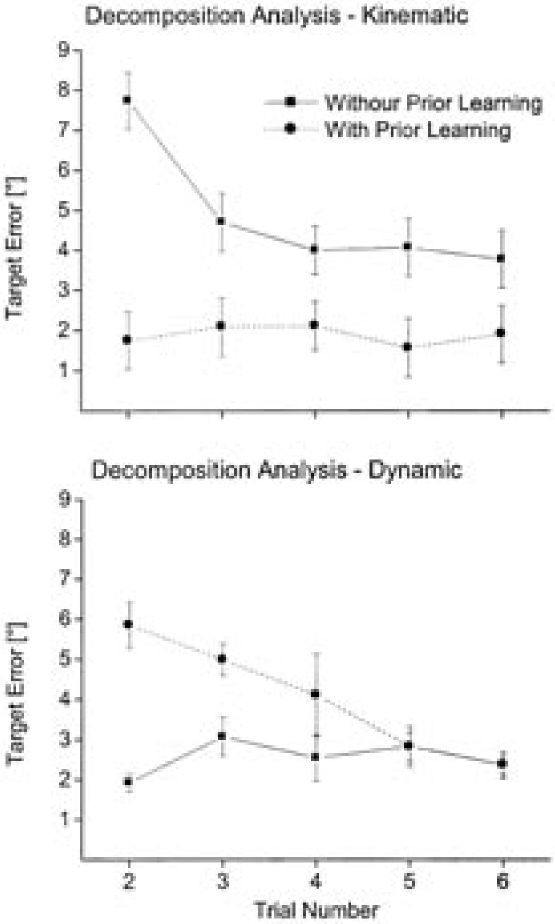

Figure 3—Decomposition hypothesis. Mean values and standard error of the target error in Trials 2–6 for the kinematic (A) and dynamic transformation (B) averaged across age groups for participants without and with prior learning of the combined transformation.

in the condition with prior learning of the combined transformation (B-C-*K*-D) and declined from Trials 2 through 6 in this condition only [trial: $F(3, 75) = 5.845$, $p = .002$; condition: $F(1, 28) = 38.290$, $p < .0001$; trial × condition: $F(3, 75) = 5.044$, $p = .004$]. There were no other significant main effects or interactions (all *p* values > .21).

In summary, for both adults and children we found a decomposition effect only for the kinematic transformation, which did not seem to be the result of practice effects. Moreover, not only was a benefit missing for the dynamic transformation, there was even a degradation of performance when the combined transformation preceded the dynamic transformation.

Comparison Between Dynamic and Kinematic Transformation

Comparing the constant error in the kinematic and dynamic transformation in the second block of the groups B-*K*-D-C and B-*D*-K-C revealed that the kinematic transformation initially led to an overshoot of the target [$\text{mean}_{\text{adults}}$: –2.27° (*SE* = 0.87°), $\text{mean}_{\text{children}}$: –3.10° (*SE* = 0.93°)], while the dynamic transformation induced target undershoot [$\text{mean}_{\text{adults}}$: 2.37° (*SE* = 0.87°), $\text{mean}_{\text{children}}$: 2.56° (*SE* = 0.87°)]. Accordingly, an ANOVA with constant target error as dependent variable revealed a significant effect of condition [$F(1, 27) = 34.004$, $p < .0001$]. Apart from the trial × age × condition interaction effect that fell just short of significance [$F(2, 51) = 34.004$, $p = .055$], all other effects were nonsignificant (all *p* values > 0.1).

Mean absolute target error across trials was 2.54° (*SE* = 0.25°) in the dynamic and 4.85° (*SE* = 0.74°) in the kinematic condition. Moreover, absolute target error declined from Trials 2 through 6 in the kinematic transformation only. The ANOVA revealed a main effect for trial [$F(4, 112) = 3.57$, $p = .009$, condition $F(1, 28) = 8.71$, $p = .006$], and an interaction between trial and condition [$F(4, 112) = 7.00$, $p < .0001$]. All other effects were nonsignificant (all *p* values > .20).

Discussion

The main results of the present study were that there was a composition benefit which was the result of learning the separate kinematic transformation immediately before learning the combined transformation. Furthermore, we found a decomposition effect only for the kinematic transformation. Both effects did not seem to be caused by practice effects. Moreover, not only was a decomposition benefit missing for the dynamic transformation, but there was even a degradation of performance when the combined transformation preceded the dynamic transformation. In neither analysis did we find an effect of age, i.e., children and adults did not differ with respect to adaptation. Finally, it was evident in the comparison analysis that the kinematic transformation induced an overshoot of the target while the dynamic transformation induced undershoot. Moreover, target accuracy was generally smaller in the kinematic transformation than in the dynamic transformation.

Our results suggest that when participants have to cope with a combined kinematic and dynamic transformation, prior learning of the kinematic transformation is helpful (composition hypothesis). Based on the results of the post hoc analysis it seems likely that the composition effect is not only based on an ability to adapt—the so-called learning to learn effect (see Bock, Schneider, & Bloomberg, 2001). Bock and colleagues (2001) showed that learning of one visuomotor transformation facilitated learning of a completely different visuomotor transformation, which was attributed to general improvements in learning capacity. It must be noted, however, that the control analysis did not reveal a significant result so that this interpretation must be supported by findings in future experiments.

One might further argue that the composition effect is based on the fact that the dynamic transformation inducing a scaling down of the amplitude and the kinematic transformation leading to an overshoot cancel each other out, thus resulting in a small absolute error. Even if this were the case, in the composition hypothesis, this canceling effect should be present both in the combined condition with and without prior learning of the separate conditions.

The decomposition hypothesis was apparently verified for the kinematic transformation: target error was small under conditions of changed kinematics after performing a combined condition. There was no such effect regarding the dynamic transformation; there was actually a degradation in performance. Participants showed a reduced target error if the combined transformation had not been performed before. This interference effect is in agreement with the results of the studies of Shadmehr and Mussa-Ivaldi (1994) and Flanagan et al. (1999). It might be at least partly attributable to the aftereffects as a result of removal of the kinematic transformation. The kinematic transformation produces larger initial errors than the dynamic transformation. As a consequence, when removing the kinematic transformation again after adaptation, aftereffects are larger than in the dynamic transformation.

The kinematic transformation was less difficult in the present study compared to the work of Flanagan et al. (1999). Nevertheless, in agreement with Flanagan and colleagues (1999), we found a smaller target error in the dynamic than in the kinematic transformation. Similarly, Worringham and Beringer (1989; 1998) argue that a spatial discrepancy between the position of the arm and the position of a “hand arrow,” i.e., a modification of gain (40°-movement is reach by 20°-movement) is more difficult to adapt to than a force field. Thus it seems to be more difficult to compute a series of joint angles necessary to reach specific targets in the environment than to compute the joint torques necessary to produce a required series of joint angles. One reason for this could be that the inverse kinematic transformation requires transformations between visual and proprioceptive coordinate systems. In contrast, the inverse dynamic transformation includes transformations within an intrinsic coordinate system, relying on proprioceptive feedback only (Gandolfo, Mussa-Ivaldi & Bizzi, 1996; Krakauer et al., 2000; Shadmehr & Mussa-Ivaldi, 1994).

It is noteworthy that adaptation in the conditions without prior learning took place rather quickly, i.e., within one trial. This stands in contrast to previous studies of Shadmehr and Mussa-Ivaldi (1994) and Flanagan et al. (1999), where adaptation was a gradual process over 10 to 20 trials. This difference in adaptation speed indicates that our transformations were less difficult than those in the previous studies. Nevertheless, similar composition and decomposition effects as in the Flanagan study suggest that it might be possible to combine/decompose different transformations. Moreover, increased task difficulty in the kinematic condition compared to the dynamic condition argues in favor of two separate models for the dynamic and kinematic transformations. The validity of this assumption cannot be verified conclusively on the basis of the present data, however. This is because we, like Flanagan et al. (1999), did not use different dependent measures for the two transformations (Krakauer, Ghilardi, & Ghez, 1999). Bock (2001), however, found that interference between transformations is comparably small when both physical transformation and kinematic variable differ as in our study (visual-position dependent versus mechanical-velocity dependent transformation).

Concerning the developmental aspect of our study we showed that children at age 11 were able to adapt to the transformations as quickly as adults. Within six trials target error of both adults and children was in the range of their target error in the baseline condition. We could not show any differences between the learning speed and accuracy of the adults and children investigated here. This is in accordance with the study of Ferrel, Bard, and Fleury (2001) who showed a similar reduction of target error across trials for 11-year-old children as for adults. Moreover, Ferrel-Chapus, Hay, Olivier, Bard, and Fleury (2002) found that the learning slopes were the same for all participants (children between the ages of 5 and 11 and adults), analyzing the adaptation performance to a visual distortion task.

Constant error was somewhat larger, however, in the children than in the adult group in the kinematic condition, indicating that the kinematic transformation seemed to be more difficult for the children than for the adults. The effect did not reach significance, however, and absolute error did not reveal any difference between children and adults. In addition, different aspects of movement kinematics might still mature at different rates (Schneiberg, Sveistrup, McFayden, McKinley, & Levin, 2002). There is, for example, a task-specific development for the coordination of grip and load forces during precision lifting. Mature movement patterns are reported to occur around the age of 8 years (Kuhtz-Buschbeck, Stolze, Joehnk, Boczek-Funke, & Illert, 1998), whereby maturation of rapid repetitive hand motions is attained at 12 years (Müller & Hömberg, 1992).

In conclusion, the present results suggest that there are two separate models for the kinematic and dynamic transformation. Furthermore, 11-year-old children seem to adapt in the same way as adults, which might suggest that a possible differentiation of kinematic and dynamic features of the motor task might already be present at that age. In further studies, however, the development of one/separate internal models must be investigated in children younger than 11 years to outline development in detail for this kind of task.

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