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RESEARCH NOTE

Breaking the flow of an action

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Abstract The present study was aimed at investigating whether the execution of a sequential action changes when the temporal contiguity between the motor steps composing it is altered. Participants were requested to reach and grasp an object and pour its contents into a container under two conditions: a 'fluent pouring' condition in which participants were instructed to execute the action fluently and an 'interrupted pouring' condition in which participants were instructed to reach and grasp the object, wait for an acoustic signal and then complete the pouring action. A 'control' condition in which participants were requested to reach and grasp the object without performing any subsequent action was also administered. Results indicate that movement duration and hand kinematics varied depending on the temporal relationship between the reach-to-grasp and the lift-to-pour phases. When a delay at object contact was introduced, reach duration was longer and the thumb/index abduction angle was greater than when such a delay was not introduced. These results are interpreted in light of 'internal model' theories suggesting that a strict temporal contiguity between the motor steps composing an action is a prerequisite for a skilful movement to be planned and executed.

Keywords Reach-to-grasp · Kinematics · Internal models · Humans · Action goal

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Introduction

For a number of decades, researchers have investigated the performance of tasks requiring sequential movements (Bernstein 1967). In these tasks, the achievement of a sequential action implied the composition of motor steps bound to each other according to a well defined syntax of actions. The concept of motor compositionality has been applied to a number of tasks including speech, handwriting, typing and piano playing in 'co-articulation' terms (Kent and Minifie 1977; MacNeilage 1980; Sternberg et al. 1978; Terzuolo and Viviani 1980; Hollerbach 1981; Viviani and Terzuolo 1983; Soechting and Flanders 1992). The term 'co-articulation' refers to the phenomenon that in a well-trained motor sequence, motor primitives are influenced by the anticipated adjacent primitives. This results in spatial and temporal overlap, which brings about the formation of a new entity differing from the sum of the elements that it comprises (Engel et al. 1997; Sosnik et al. 2004). What can be gained from the operational definition of 'co-articulation' is that when the planning of a movement encompasses several segments at a time, the execution of one segment might be altered to facilitate the execution of subsequent segments for the achievement of a specific goal.

Support for this contention comes from a series of studies showing that the fulfillment of a specific goal is an important determinant for the planning and execution of the motor sequence subtending reach-to-grasp movements (Ansuini et al 2008; Armbrüster and Spijkers 2006; Marteniuk et al. 1987). For instance, Marteniuk et al. (1987) asked subjects to reach for an object and to either fit it into a similarly sized opening or to throw it away. While the two conditions did not differ in terms of the initial task requirements, kinematic analyses for the first reach-to-grasp phase revealed lower peak velocities and longer deceleration periods for the 'fit' than for the 'throw' condition. Similarly, Armbrüster and Spijkers (2006) reported that the amplitude of peak aperture was larger and the amplitude of peak deceleration was higher when the reach-to-grasp movement phase was followed by either a throwing or a placing movement than by a lifting or a raising condition.

An interesting implication of these findings is that the action sequence subtending a reach-to-grasp movement is not a concatenation of individually planned and executed motor components, but rather an overarching unit that supersedes these components so as to fluently achieve a temporally extended task. Therefore, it might well be that when motor fluency is prevented the motor system loses the ability to plan a given action sequence globally on the basis of the end-goal but instead plans it discretely on the basis of individual action steps. This aspect in particular outlines the novelty of the present work given that, while the phenomenon of the concatenation of the motor elements has been frequently investigated, voluntary interruption of a composite motor sequence has never been previously considered.

Here, we test this possibility by asking participants to reach and grasp an object and pour its contents into a container while varying the temporal contiguity of the 'neighboring' movements composing the pouring action sequence. The 'pouring' task appeared to be ideal for testing our hypothesis, since it has sequential features and represents an action routinely performed during daily activities. Further, as previously demonstrated, it is possible to reveal a clear end-goal effect on hand kinematics when the same action (i.e., grasping a bottle) is performed with the intent of pouring its contents rather than of simply grasping it (Ansuini et al. 2008). To test for the 'temporal contiguity' hypothesis, we contrasted a condition in which participants performed this task fluently with a condition in which the same action was 'interrupted' (i.e., with an interruption between the grasp and lift-to-pour action segments). We reasoned that if the motor system plans and executes the considered motor sequence on the basis of its temporally extended goal, regardless of the temporal relationship among its components, no differences should be found when comparing the 'fluent' and the 'interrupted' conditions. Conversely, a difference between these two conditions (if found) would favor the opposite conclusion. A caveat concerning this hypothesis regards the nature of the 'interruption.' Because, in the 'interrupted' condition, participants should maintain their hand stationary on the target object for a certain period of time, it might be said that possible differences could simply stem from the need to stop the action. Therefore, to understand whether the presence of an interruption might be responsible for possible differences across relevant conditions, we compared a 'control' condition, in which participants were requested to reach toward and merely grasp the target object, with the 'interrupted' condition. If differences from such a comparison arise, then it might be possible to conclude that it is not the presence of the interruption, which may determine possible differences between the 'fluent' and the 'interrupted' conditions. In turn, this would allow us to understand whether the first reach-to-grasp step of the 'interrupted' pour condition is planned and executed as in the 'control' condition. Importantly, such a comparison would also allow us to determine whether an interruption has the ability to 'wash-out' the influence of the end goal on the control of a sequential action.

Method

Participants

Eight right-handed subjects (five females and three males, mean age 23 years) took part in the experiment. All participants reported normal or corrected-to-normal vision, were naïve as to the purpose of the experiment, and gave their informed consent to participate in the study. The experimental procedures were approved by the Institutional Review Board at the University of Padua and were in accordance with the Declaration of Helsinki.

Material and apparatus

The target was a copper amphora filled with 350 ml of water (see Fig. 1a) located on a 7 cm high plastic support at a 30 cm distance from the hand start position (Fig. 1a). Hand posture was measured by resistive sensors embedded in a glove (CyberGlove, Virtual Technologies, Palo Alto, CA, USA), worn on the subject's right hand.

The sensors' maximum nonlinearity was 0.62% of the full range of hand motion. The sensors' resolution was 0.5°, which remained constant over the entire range of joint motion. The output of the transducers was sampled at 12-ms intervals. Data were low-pass-filtered with a cut-off frequency of 8 Hz, using a second-order Butterworth filter. Metal wires were inserted into the volar surface of the CyberGlove so as to cover the length of the five digits, together with both the thenar and the hypothenar eminence of the hand. Before starting the experiment, the 'baseline' thumb/index abduction angle for each participant was determined. This was achieved by setting the 'baseline' value at 0° when the participants' hand was positioned flat on the working surface with a preset thumb/index abduction angle equal to 22°. The thumb/index abduction angle aperture was assigned negative values. At the beginning of each trial, subjects placed their right hand on a starting platform within which a pressure switch was embedded (i.e., the starting switch). Participants naturally reached toward

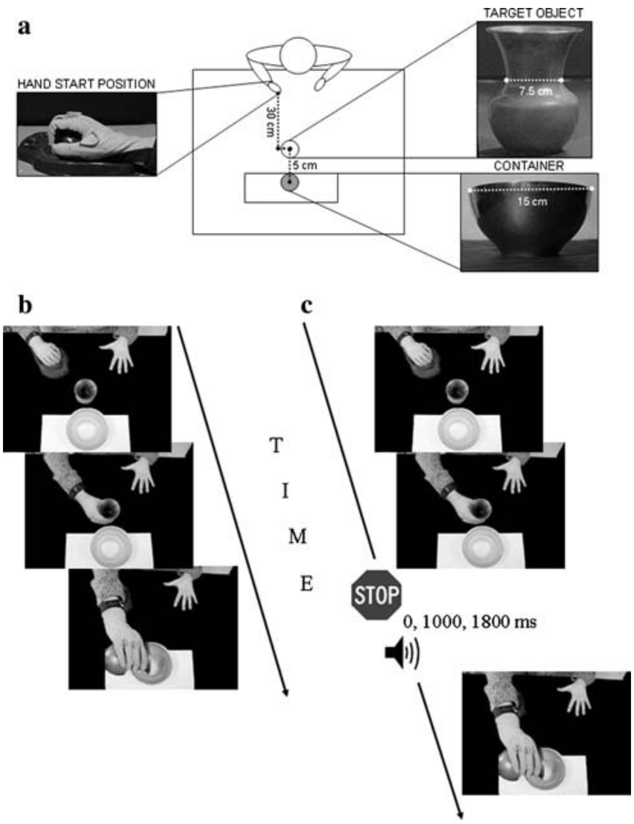

Fig. 1 **a** The hand starting position, the top view of the experimental setup, the target object, and the container in which the object's contents was poured. **b**, **c** Schematic representation of the sequence of events for the 'fluent pouring' and the 'interrupted pouring' conditions, respectively

and grasped the target object by opposing the thumb to the four fingers of her/his right hand after hearing an auditory signal (880 Hz; duration = 200 ms). This signal was termed the 'start' signal. When the metal wires mounted on the CyberGlove entered into contact with the target, another sound (600 Hz; duration = 200 ms), termed the 'grasp' sound, was delivered at specific time delays: (1) at object contact (0 ms); (2) 1,000 ms after the hand had contacted the object; and (3) 1,800 ms after the hand had contacted the object. The occurrence of the 'grasp' sound at random intervals ensured that participants could not predict its occurrence and perform the 'interrupted' condition automatically.

Procedure

Participants underwent three experimental conditions:

1. A 'control' condition. In this condition, participants were requested to perform a reach-to-grasp action toward the target. Following contact with the object, participants were requested to bring the hand back to the starting position. All participants were explicitly told not to perform any subsequent action. The 'grasp' sound was only presented on target contact (0 ms).
2. A 'fluent pouring' condition. In this condition, participants were requested to perform a reach-to-grasp action toward the target and then pour its contents within a plastic container (see Fig. 1b). The 'grasp' sound could be delivered on target contact (0 ms), or 1,000 or 1,800 ms after target contact in a fully randomized fashion. However, participants were explicitly told to perform the action fluently, without taking any notice of the 'grasp' sound.
3. An 'interrupted pouring' condition. In this condition, participants were requested to perform a reach-to-grasp action toward the target and were explicitly instructed to wait for the 'grasp' sound to complete the pouring action. The 'grasp' sound varied in delivery for target contact (0 ms), or 1,000 or 1,800 ms after target contact in a fully randomized fashion (see Fig. 1c).

For each trial of all conditions, the experimenter visually monitored the participants' performance to ensure their compliance to the experimental procedures. All trials in which participants anticipated either the 'start' or the 'grasp' sound (when relevant) were considered error trials. Similarly, trials in which participants did not properly fulfill the experimental task were considered errors (e.g., performing a pouring action despite being given instructions to simply grasp the target object, or not grasping the target object using all five fingers).

Participants performed a total of 50 trials, 10 trials for the 'control' condition, 10 trials for the 'fluent pouring' condition, and 30 trials for the 'interrupted pouring' condition (10 trials for each 'grasp' sound time delay, i.e., 0, 1,000, 1,800 ms). The order of the trials was fully randomized. However, participants were always informed about what the upcoming condition was going to be and they all underwent six practice trials (two for each condition) at the beginning of the experiment.

Analysis

The dependent measures thought to be specifically relevant to test the experimental hypotheses were reach duration and the thumb/index abduction angle. Reach duration was chosen because it is a measure, which is sensitive to the presence or absence of a subsequent action following grasp (Gentilucci et al. 1997; Johnson-Frey et al. 2004). Therefore, the explicit requirement to interrupt the flow of action should be evident in this measure. Reach duration was calculated as the time interval between the release of the starting switch and the time at which the fingers contacted the object. Thumb/index abduction angle was chosen because this measure appears to be sensitive to situations in which grasping an object is the intermediate step of a coordinated reach-to-grasp action (Ansuini et al. 2008). The main reason for using different time delays for the presentation of the 'grasp' sound during the 'interrupted pouring' condition was to ensure that participants relied on the sound to start the subsequent action and did not start the movement automatically. Therefore, we did not expect any significant difference depending on the extent of the delay. To test this hypothesis, we performed two analyses of variance (ANOVAs) on reach duration and the thumb/index abduction angle with 'Delay' (0, 1,000, 1,800 ms) and 'Delay' (0, 1,000, 1,800 ms) and 'Time' (from 10 to 100% of the reach, at 10% intervals) as within-subject factors, respectively. These analyses revealed that there were no differences in reach duration and in the thumb/index abduction angle when comparing trials at each time delay (i.e., 0, 1,000, 1,800 ms) ('Delay': $F_{(2,14)} = 0.109$, $P > 0.05$ for reach duration and 'Delay': $F_{(2,14)} = 1.657$, $P > 0.05$; 'Delay by Time': $F_{(18,126)} = 1.095$, $P > 0.05$ for thumb/index abduction angle). Consequently, we randomly selected trials from each time delay and we used this new pool of data for the 'interrupted pouring' condition. To test for possible differences in reach duration as a function of experimental condition, an ANOVA with 'Condition' ('control,' 'fluent pouring,' 'interrupted pouring') as a within-subjects factor was performed. To assess how and to what extent the abduction angle between the thumb and the index finger differed across experimental conditions, we performed an ANOVA with 'Condition' ('control,' 'fluent pouring,' 'interrupted pouring') and 'Time' (from 10 to 100% of the reach, at 10% intervals) as within-subjects factors. Simple effects were used to explore the means of interest. Bonferroni corrections (alpha level: $P < 0.05$) were applied. Errors were not analyzed given that, following the established criteria reported above, there were none.

Results

Despite maintaining as constant the distance between the hand starting position and the target, the time taken by the hand to cover this distance differed depending on the type of experimental condition ($F_{(2,14)} = 19.603$, $P < 0.0001$). Specifically, post-hoc contrasts revealed that reach duration was shorter for the 'fluent pouring' than for the 'interrupted pouring' condition (1,304 ms vs. 1,886 ms, respectively) (see Fig. 2a). Furthermore, reach duration was significantly longer for the 'interrupted pouring' than for the 'control' condition (1,286 ms) (Fig. 2a).

The analysis performed on the thumb/index abduction angle revealed a significant main effect of 'Condition' ($F_{(2,14)} = 7.358$, $P < 0.008$). Post-hoc comparisons indicated that this measure was smaller for the 'fluent pouring'

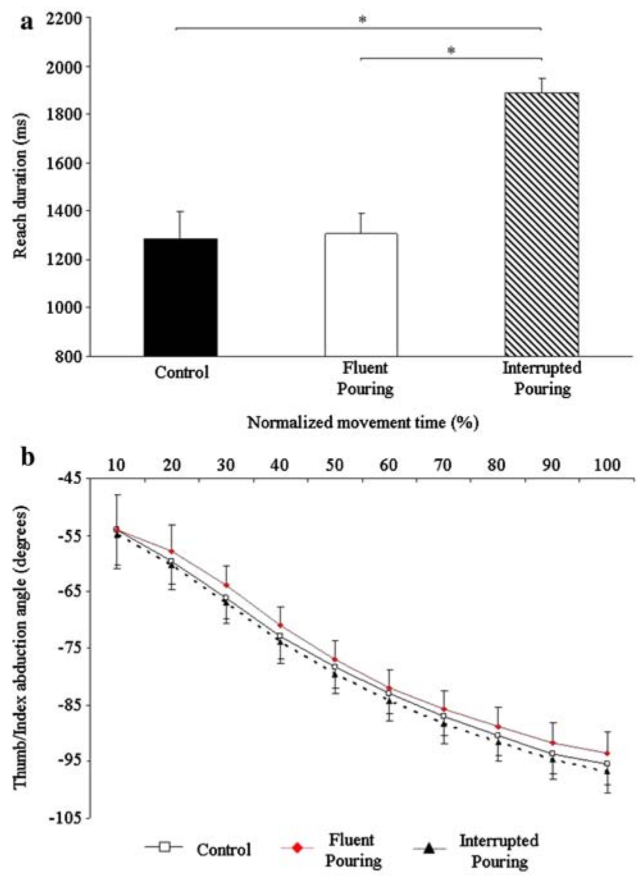

Fig. 2 **a** Reach duration in milliseconds (ms) for the three experimental conditions. *Bars* represent standard error of means (SEM). **b** Time course of thumb/index abduction angle for each experimental condition. An increase in negative values signifies greater abduction. Data are averaged across trials and participants. *Bars* represent SEM

(−76°) than for both the 'interrupted pouring' and the 'control' condition (−79° and −78°, respectively) (see Fig. 2b). The main effect of 'Time' was also significant ($F_{(9,63)} = 92.773$, $P < 0.0001$). Broadly speaking, the thumb/index abduction angle progressively and significantly increased up to the time the object was grasped (Fig. 2b). The interaction 'Condition' by 'Time' was not significant ($F_{(18,126)} = 1.291$, $P > 0.05$).

Discussion

The goal of the present study was to determine whether varying the temporal contiguity between the segments composing a motor sequence alters how this sequence is performed. It was found that introducing a delay between the first and the second segment of a pouring action brought differences in how the hand approached the object with respect to when no delays were introduced. Specifically, we demonstrated that when a pouring action was interrupted the reach duration and the thumb/index abduction angle increased with respect to when the same movement was performed fluently. Further, when the ‘interrupted pouring’ condition was compared with the ‘control’ condition, reach duration was longer for the former than for the latter, whereas no difference in terms of abduction angle was found.

At first sight, these effects might be explained in terms of biomechanical differences between the dynamic ‘fluent’ and the ‘interrupted’ conditions. For instance, it might well be that the increase in movement duration for the ‘interrupted’ compared to the ‘fluent’ condition would reflect the need of a longer time and of a greater safety margin for the former condition. This is because, for the ‘fluent’ condition, the arm may not come to a complete stop during grasping the target, whereas this would be the case for the ‘interrupted’ condition in which the breaking phase is more pronounced. However, if this were the case, the ‘control’ condition, which also required the action to be halted at object contact, should have brought similar results as those for the ‘interrupted’ condition. Similarly, if the reported effects stem from the additional demands of correct placement at the target determined by the need to perform a subsequent action segment for the ‘interrupted’ condition, then no differences should be evident when comparing the ‘interrupted’ with the ‘fluent’ condition. Therefore, biomechanical factors might not exclusively account for the present findings.

At this stage, it is tempting to advance an explanation, which considers higher cognitive processes. In this view, the lengthening in reach duration found for the ‘interrupted pouring’ condition might reflect the occurrence of an active inhibiting process. For the ‘interrupted pouring’ condition, participants knew that, at some stage, they would be requested to pour the contents of the target once grasped. Therefore, it is reasonable to assume that the motor control system might select a given model-movement (i.e. lift to pour) and set the time at which the schema for this model should be delivered. An active inhibiting process might guarantee that the model occurring after the reach-to-grasp phase would not be delivered too early, thus compromising task performance. In other words, the very fact that such a model had to be operationalized after the object was grasped (following the sound indicating to lift the object) required a ‘halt’ in the lifting phase. Such active inhibition process occurred during the unfolding of the reach-to-grasp movement and produced a sort of ‘interference,’ which translated into the observed lengthening of reach duration.

A natural question is, why such an inhibitory process does not take place for the ‘fluent pouring’ condition, which also implies two movement steps just as the ‘interrupted pouring’ condition does. We suggest that when there is temporal contiguity between the different movement phases, the motor system finds it more effective to operationalize a representation in which the different motor steps are ‘composed’ rather than individual representations for each motor step.

The notion of internal models may provide a suitable theoretical framework to explain what is proposed above. In this regard, the ‘temporal-contiguity’ effect might indicate the difficulty of using merged internal predictive models for controlling ‘broken’ actions. The idea is that the motor control system makes use of internal models, which can be conceptually regarded as motor primitives, to anticipate the consequences of our own actions (Wolpert and Kawato 1998). According to the dominant interpretation of this theory, the motor system deals with multiple sensory–motor transformations, which might be adaptively ‘merged’ if presented in strict temporal succession (Blakemore et al. 1998; Kawato 1999). According to this postulation, we found that, under the interrupted circumstances, the merging of the two steps composing the action considered here is somewhat prevented. Error signal derived from sensory feedback related to the attainment of the first motor act (i.e., reach-to-grasp movement) may be responsible for the reported effects.

Previous evidence suggests that when digits initially contact an object, ensembles of tactile afferents provide early information about both the frictional status of the contact (Johansson and Westling 1987) and the direction of fingertip forces (Birznieks et al. 2001). At this time, the proprioceptive feedback furnishes information regarding the body state such as, for instance, wrist acceleration or position of the fingers on the object. All this ‘actual’ sensorial information is matched with the predicted sensory feedback and if differences are detected an error signal is generated (Wolpert and Kawato 1998). This ‘error’ mechanism is fundamental for updating the motor plan initially selected on the basis of the forward model and for providing initial state information for the subsequent phase (Flanagan et al. 2006). Applying these concepts to the present data, it might well be that when the transition between the first and the second movement phase is interrupted, the use of such a monitoring-correction mechanism is altered. Using the error signal derived at the time the object is grasped for evaluating the sensorial background for the successive lifting phase may cause an error, because the sensorial information might change during the interruption. For instance, such a change may occur at the level of the grip forces, which are necessary for lifting the object and heavily depend on hand acceleration (e.g., the greater the acceleration, the greater the preplanned force when lifting the object) (Johansson and Westling 1987). Consider the present ‘interrupted pouring’ condition: if the motor system uses the information derived from hand acceleration at the moment the hand makes contact with the object (and the error signal derived from it) for preplanning the forces suitable for lifting that object, then this may result in an erroneous force application, because during the interruption, the acceleration of the hand might change. In other words, the predicted sensory feedback for the first movement phase might be time-locked with the state that it allows to estimate (that relating to the second phase). When this time-lock procedure is broken (such as in the 'interrupted pouring' condition), merging the sensory–motor transformations related to grasping and lifting into one 'pouring' internal model would not be adaptive. Therefore, what we have observed for the 'interrupted pouring' is an action, which is planned on the basis of individual rather than merged representations of motor steps. Support for this contention comes from the results obtained for the 'control' condition. Indeed, if the reach-to-grasp movement phase for the 'interrupted pouring' condition was planned, giving no consideration to a potential subsequent action, then the kinematics should be the same as for the 'control' condition in which no subsequent movement was considered. This is what we found; when comparing the 'interrupted pouring' and the 'control' conditions, the thumb/index abduction angle did not differ confirming that in both circumstances the prehensile movement was planned as if the action to be performed following grasping would have been 'washed-out.'

In conclusion, the present findings suggest that the temporal structure characterizing complex motor acts is an important determinant for the planning and execution of a prehensile action. Further research is needed to fully clarify how the CNS considers time intervals amongst different movement phases when planning a sequential action.

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