Journal of Motor Behavior, 2009, Vol. 41, No. 1, 10–15

Immediate Movement History Influences Reach-to-Grasp Action Selection in Children and Adults

Samuel W. Kent[1], Andrew D. Wilson[1], Mandy S. Plumb[2], Justin H. G. Williams[1], Mark Mon-Williams[1]
[1]College of Life Sciences and Medicine, University of Aberdeen, United Kingdom. [2]Faculty of Health and Social Care, School of Health Sciences, Robert Gordon University, Aberdeen, United Kingdom.

ABSTRACT. Action selection is subject to many biases. Immediate movement history is one such bias seen in young infants. Is this bias strong enough to affect adult behavior? Adult participants reached and grasped a cylinder positioned to require either pronation or supination of the hand. Successive cylinder positions changed either randomly or systematically between trials. Random positioning led to optimized economy of movement. In contrast, systematic changes in position biased action selection toward previously selected actions at the expense of movement economy. Thus, one switches to a new movement only when the savings outweigh the costs of the switch. Immediate movement history had an even larger influence on children aged 7–15 years. This suggests that switching costs are greater in children, which is consistent with their reduced grasping experience. The presence of this effect in adults suggests that immediate movement history exerts a more widespread and pervasive influence on patterns of action selection than researchers had previously recognized.

Keywords: action selection, bias, immediate movement history, reach-to-grasp

Human adults possess an incredible repertoire of skilled movements. This repertoire provides flexibility in the face of variable task demands with the computational (time consuming) expense associated with selecting the appropriate action. It is crucial for movement scientists to understand the process of *action selection* (how and why one specific action is chosen from the repertoire) and the factors that bias and constrain that process and make it a solvable problem.

Action selection can be constrained in several ways. First, skilled adults can exert voluntary control and choose to execute a particular action. Second, action selection can be biased by the physical nature of the environment (e.g., an object's shape and size limits the possible movements). In particular, object affordances elicit specific action responses (e.g., a mug is likely to produce a grasp; Arbib, 1985; Gibson 1966, 1979). Nevertheless, these task characteristics do not specify precisely how an action should be executed—many actions can be implemented through numerous different movements (e.g., grasping the mug might involve one of the numerous possible combinations of joint angles). The action must therefore be constrained further to allow a specific implementation of the movement to be selected. Past research has demonstrated two factors that bias specific reach-to-grasp action implementation: minimal rotation (MR: Cruse, 1986; Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990; van Bergen, van Swieten, Williams, & Mon-Williams, 2007) and end-state comfort (ESC; e.g., Rosenbaum et al., 1990).

Van Bergen et al. (2007) found that adult participants were generally biased toward an action that minimized wrist rotation when they were asked to grasp (but not turn) a piece of dowelling. This MR bias caused participants to pronate their hand in grasps where the thumb ended above the index finger and to supinate the hand when the thumb needed to end under the finger. Rosenbaum and colleagues investigated the consequences of a subsequent goal on initial movements and found that altering the goal of a secondary movement affected the action selected for an otherwise constant initial reach-to-grasp task (Cohen & Rosenbaum, 2004; Rosenbaum, Heugten, & Caldwell, 1996; Rosenbaum et al., 1990; Rosenbaum, Meulenbroek, & Vaughan, 1996; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993). Adult participants would begin a movement in an uncomfortable, maximally rotated position if that meant they would finish the task in a comfortable, neutral posture. This was described as the ESC effect, and it reflects the impact that subsequent movements may have on action selection at an earlier stage of the task.

Though the effect of subsequent task demands has been explored, the effect of past action choices is much less studied. Nevertheless, the effects of movement history on action selection in infancy have been well demonstrated in the form of the classic "A not B" error. Infants reach incorrectly for a hidden object primarily as a function of where and how often they have just reached (Thelen, Schöner, Scheier, & Smith, 2001). Infants show a tendency to perseverate with the action just produced (the reach to Location A) even in the face of a strong reason to switch to a new action (the unambiguous presentation of the object at Location B). The infants in most of these studies are 7–12 months of age; after this age, this form of error disappears, although Spencer, Smith, and Thelen (2001) have elicited perseveration in older children (2 years). Perseveration does occur in adults, but it is generally a feature of neurological impairment in adults with frontal lobe injury (Joseph, 1999) and is generally quite overt in these cases. The question remains whether immediate movement history influences behavior in more subtle ways in typical adults and older children.

There are two reasons to think that it might. First, theoretically, there are computational advantages, even for a skilled

Correspondence address: Andrew D. Wilson, College of Life Sciences and Medicine, University of Aberdeen, Aberdeen, AB24 2UB, United Kingdom. E-mail address: andrew.wilson@abdn.ac.uk

adult, in modifying a previous action rather than selecting a new action class (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Second, there is empirical evidence that immediate movement history affects adult behavior. Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987) demonstrated kinematic consequences of past reaches on subsequent reaches as a function of the task requirements of the previous reaches (e.g., precision constraints). Rosenbaum, Weber, Hazelett, and Hindorff (1986) demonstrated interference effects on a motor response as a function of the most recent response, and Jax and Rosenbaum (2007) and Van Der Wel, Fleckenstein, Jax, and Rosenbaum (2007) more recently showed that the spatial path taken by the hand is susceptible to priming, suggesting that the current action is dependent on a previous one.

There have also been articles that have explicitly investigated whether a person is more likely to produce a suboptimal behavior as a function of immediate past experience. Cohen and Rosenbaum (2004) asked participants to grasp a cylinder resting on one shelf, move it to a second shelf at a different height before removing their hand, and then return the cylinder to the first shelf. Cohen and Rosenbaum found that the second grip was biased toward the initial grip location despite this being a suboptimal grasp location. De Lussanet, Smeets, and Brenner (2001, 2002) explored an interception task and found clear evidence of previous successful interceptive behavior influencing subsequent action selection. These studies are insightful, but all involved measuring actions selected to meet secondary goals. A suboptimal strategy might be used under these conditions for several reasons (e.g., if attention resources are directed toward other aspects of the task, or if the demands of the secondary task are incorporated into the initial reach).

One key study on the role of recent movement history is Kelso, Buchanan, and Murata (1994) which examined performance in a simple "reach to grasp and turn" task, in which the initial orientation of the target was either systematically varied (clockwise or counterclockwise) or randomly varied. Kelso et al. showed a switch in the turning movement from pronation to supination, critically demonstrating that the switch occurred at different positions for the two systematic conditions. The switch occurred later in the systematic conditions than in the random condition (i.e., further clockwise in the clockwise condition and vice versa in the counterclockwise condition). Kelso et al. described this as *hysteresis*, a dynamical systems term that describes the tendency of a system to persist in a current state.

Immediate past history does clearly seem to bias complex movements (e.g., obstacle avoidance) or movements with secondary requirements. However, all of the previous research has measured performance on a secondary task element (e.g., the turn in Kelso et al.'s (1994) reach-to-grasp-and-turn task). As described above, these secondary task requirements introduce additional biases for action selection; for instance, MR may be superseded by ESC. To carefully address the issue of immediate past history, researchers should look at performance in a task where just one bias (e.g., MR) would ordinarily dominate. In the current study, we wanted to determine whether previous movement history would influence performance on a simple reach-to-grasp task where there was no secondary goal; all other things being equal, we would expect the MR bias to drive action selection. Any systematic change in behavior can therefore be attributed to movement history. Prehension is a task neurologically intact adults find quite trivial to perform, and demonstrating an effect of movement history here would confirm that it is a significant bias on action selection (perseveration in grip aperture scaling has been demonstrated [Dixon, Li, & Read, 2007] suggesting that even simple prehension may be susceptible to movement history effects).

We were also interested in exploring whether immediate movement history would have a greater effect in children. Switching costs are generally a function of the stability with which that target movement can be made (e.g., Scholz & Kelso, 1990). Children are still refining their movement skills (e.g., Kuhtz-Buschbeck, Stolze, Johnk, Boczek-Funcke, & Illert, 1998; Mon-Williams et al., 2005; Tresilian, Mon-Williams, Coppard, & Carson, 2005) and the costs of switching between movement patterns are therefore likely to be higher because the target pattern is not as well practiced as it is in adults. We might therefore expect a greater reliance on past successful action in children.

EXPERIMENT 1

Method

Participants

We recruited 68 students from the University of Aberdeen, aged 19–25 years. Six participants were left-handed as indexed by items from the Edinburgh Handedness Inventory. All experiments were conducted with ethical approval from the local review board and in accordance with the Declaration of Helsinki.

Procedure

Participants sat in front of a table with a piece of dowelling (5 cm long) mounted on a stand 18 cm above the table surface and 25 cm from the table edge. The dowelling had one red end and could rotate in the coronal plane while fitting snugly in the stand. The task involved reaching and grasping the cylinder with the thumb always in contact with the red end of the cylinder. After explaining the rules ("thumb must be on the red end, index finger on the other end") the experimenter demonstrated one reach-to-grasp movement with the red end of the dowelling at the position equivalent to 9:00 on a clock face (0° in Figure 1). Participants began the experiment with the thumb and index finger of their dominant hand together and resting on the edge of the table in the midline and were asked to reach and grasp the dowelling "quickly and accurately" five times in a row at each orientation and to return to the start position between reaches. This procedure

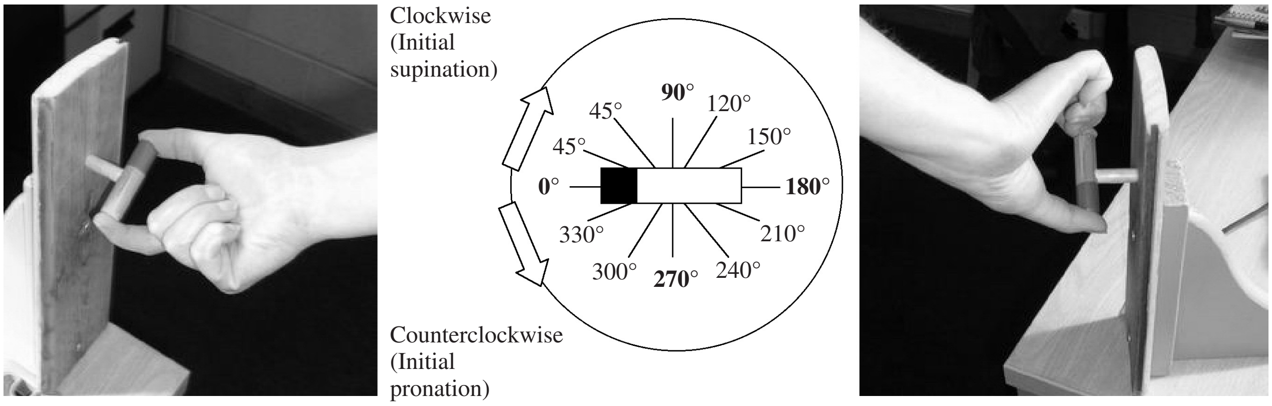

FIGURE 1. Schematic of the apparatus. The dowelling in the middle had a piece of red tape at one end (black in the figure), on which participants were instructed to place their thumb on each trial. The dowelling is shown in the common starting location for both clockwise and counterclockwise positions. The clockwise group began with supination (rolling the hand away from the midline—left) whereas the counterclockwise group began with pronation (rolling the hand toward the midline—right).

was then repeated with the dowelling rotated from its primary position as follows: 45, 90, 120, 150, 180, 210, 240, 270, 300, 330, and 360° (see Figure 1). Each session took approximately 10 min.

There were three conditions, administered separately to three groups. In the random condition ($n = 28$), the different dowelling orientations were presented in a randomized order that was different for each participant. In the clockwise condition ($n = 22$), the red end of the dowelling was first placed in the 0° orientation, then rotated clockwise in increments of 45° for the first two positions and 30° thereafter. This meant participants made five reaches to 45°, followed by five reaches to 90°, and so on. In the counterclockwise condition ($n = 18$), the red end of the dowelling was first placed in the 0° orientation, then rotated counterclockwise in increments of 45° for the first two positions and 30° thereafter. This meant participants made five reaches to 315°, followed by five reaches to 300°, and so on. The target positions were reversed for left-handed participants.

For most orientations, it was possible to reach to grasp the dowelling in one of two ways: by pronating or supinating the hand. Supination involves rotating the hand away from the midline; pronation is rotation toward the midline (see the photos in Figure 1). When the target was oriented 45° clockwise, the MR bias predicts people will supinate through 45° rather than pronate through 315°. The MR bias predicts the opposite result when the target is oriented 45° counterclockwise. Thus, in the clockwise condition, the optimal MR strategy is to supinate the hand until the 210° orientation, and then switch to pronation and vice versa for the counterclockwise condition. We predicted that movement history would have no net effect in the random condition, which therefore served as the baseline. Grip was scored as pronation or supination on each reach by the experimenter, and we measured the point at which participants switched from their initial movement (pronation or supination) to the other movement and compared this threshold for the random group to the threshold for the clockwise and counterclockwise groups.

Results

As predicted on the basis of the MR bias, all participants in the clockwise condition used supination to grasp the dowelling in its first location (red end at approximately 10:00 on a clock face), whereas all the participants in the counterclockwise condition used pronation to grasp the dowelling in its first location (red end at approximately 8:00 on a clock face). The key measure was the position at which participants transitioned from supination to pronation or from pronation to supination. The majority of participants (38 of 46) transitioned between 90 and 270°, although there were examples of participants who transitioned at every subsequent position. For each participant, we computed the frequency of supination at each orientation and determined the average transition point between 0% supination and 100% supination by taking the 50% point on a logistic regression curve. Figure 2 shows the average data for the three groups plotted in this manner.

We performed an analysis of variance on the transition point data for each participant, with group (clockwise, counterclockwise, random) as a between-participants factor. There was a main effect of group, $F(2, 65) = 37.5$, $p < .01$, and post hoc analyses (using the Bonferroni correction for multiple comparisons) showed that all three groups were significantly different from each other (all ps $< .02$). In comparison with the random control group (mean transition = 217.5°, $SD = 25.03°$), the clockwise group transitioned at a greater angle (i.e., supinated longer; mean transition = 246.42°, $SD = 42.71°$) and the counterclockwise group transitioned at a lesser angle (i.e., pronated longer; mean transition = 135.0°, $SD = 58.43°$), showing that the transition point had been biased in the appropriate direction as a function of immediate past reach history.

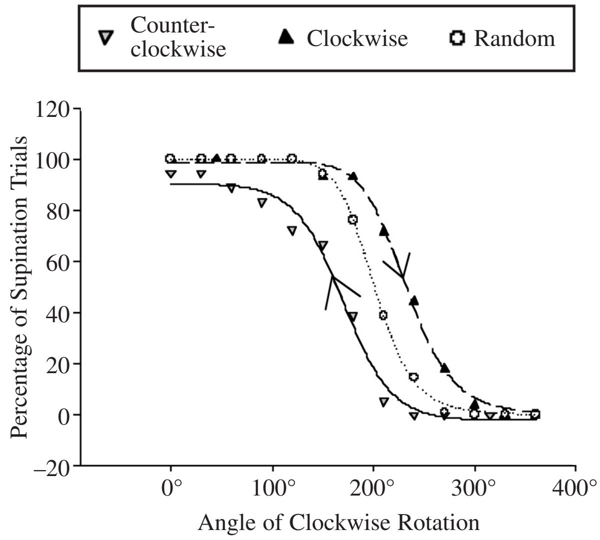

FIGURE 2. Logistic regression curves for the group data in Experiment 1. Note the arrows: the clockwise group began supinating (left) and eventually transitioned to pronation. The counterclockwise group began pronating (right) and eventually transitioned to supination.

EXPERIMENT 2

Method

Participants

We recruited 74 children aged 5–15 years. Fifty-six of the children were aged 5–11 years (27 boys, 29 girls, 6 left-handers) and were recruited from a primary school. Eighteen children were aged 12–15 years (8 boys, 10 girls, 1 left-hander) and were recruited from a high school. Information sheets were distributed to classes 2 weeks before testing started. Pupils who returned a parental consent form agreeing to participation were taken out of class to carry out the experiment. We distributed 200 letters and information sheets, and we received 105 signed parental consent forms. All included children were reported to be performing satisfactorily at school with no indication of any problems.

Procedure

The apparatus and procedure were identical to those used in Experiment 1. The dowelling was small enough that none of the children had any difficulty in grasping it. One difference was that the children only performed the task with the dowelling rotated clockwise. The three conditions were too much to ask of the younger participants, and this single condition allowed us to compare the children's transition point under the influence of a systematic past history relative to that observed in the adults.

Results

We first explored whether there was a reliable effect of age across the children. A linear regression of age and transition angle showed no reliable relation between age and transition angle ($r^2 = .155$). We therefore considered the data from all of the children together in subsequent analyses.

We compared the children to the clockwise and random adult groups. Figure 3 shows the group data for the adults in the random and clockwise condition from Experiment 1 together with the clockwise condition data from the children.

Four children (aged 15, 10, 10, and 4 years of age) did not switch at all, even after reaching five times to 360° (requiring them to rotate their hand by a very uncomfortable 360°). We performed an analysis of variance on the transition point data for all the subjects (including those who didn't transition—although they were outliers, their performance was clearly data rather than noise and we had no reason to exclude them) with group (adult clockwise, adult random, child clockwise) as a between-subjects factor. There was a main effect of group, $F(2, 121) = 20.5$, $p < .01$, and post hoc analyses (again using the Bonferroni correction for multiple comparisons) showed that all three groups were significantly different from each other (all ps < .01). We already saw that the adult clockwise group transitioned later than the adult random group, so we performed a two-tailed independent sample t test on the transition point data for the adult and children clockwise groups as a stronger post hoc analysis. The result showed that children switched from supination to pronation 26.41° later than the adults, $t(100) = 3.05$, $p < .01$.

GENERAL DISCUSSION

We investigated whether immediate movement history is a significant bias in action selection during a reach-to-grasp task. Adults and children all demonstrated this bias—an individual who started the experiment using one movement

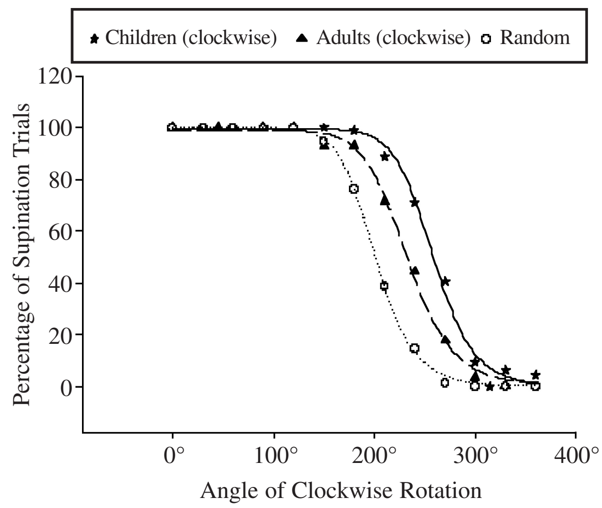

FIGURE 3. Logistic regression curves for the group data in Experiment 2, comparing the adult clockwise group to the child clockwise group, with the adult random group data for comparison. Both clockwise groups started at the left and transitioned later than the random group.

form (pronation or supination) continued to use that movement pattern at positions where the random group selected a different, more efficient reach-to-grasp movement. Children showed the bias more strongly than adults, suggesting that they depend more heavily on previously successful actions than do skilled adults. The overall conclusion is that there is indeed an immediate movement history bias contributing to the selection of an action in prehension, in addition to the previously identified MR and ESC prehension biases (Rosenbaum et al., 1990; van Bergen et al., 2007) and other demonstrations of history effects (e.g., de Lussanet et al., 2001, 2002; Jax & Rosenbaum, 2007; Kelso et al., 1994).

Adults are highly skilled at producing simple reach-to-grasp movements. It is therefore of great interest that we were able to produce an effect of immediate movement history that led to adults selecting a suboptimal movement. Clearly, even for a highly skilled adult, generating a different class of movement has associated costs in terms of computation time, and these costs evidently had behavioral consequences in this experiment (as measured by the changing threshold in the systematic conditions). In our task, the cost of stability (persisting in an inefficient, non-MR movement) was less than the cost of switching for quite some time (up to 82° in the counterclockwise condition). This leads us to suggest that past movement history constitutes a strong and pervasive influence on action selection that spans many levels of action complexity, from prehension (as in the current study) to more difficult tasks (e.g., obstacle avoidance; Jax & Rosenbaum, 2007; Van Der Wel et al., 2007)

The experiment shows that children who initially selected one movement changed later than adults did in an identical task. The younger group therefore showed an increased preference for a non-MR movement rather than a switch to a new movement. This is consistent with the greater cost of switching in individuals with less mature motor systems, meaning that gains in economy of movement must be greater before switching is perceived as worthwhile. This result obviously has parallels with the infant A-not-B perseveration error, which Thelen and colleagues have shown to be almost entirely a function of recent motor history (Thelen et al., 2001). It is interesting that there was no developmental trend in the current study—all of the children across the wide age range tested showed the same basic pattern. We predicted a higher proportion of adultlike behavior in the older children, but either the children were not old enough or the measure was not sensitive enough to show this effect. Previous movement history therefore appears to be a strong bias influencing immature (younger) actors (although it should be noted that the pragmatic difficulties of running the full design with the children does limit the degree to which we can generalize the results. However, the goal was simply to demonstrate how poorer movement skill affected an actor's reliance on immediate movement history and the results do demonstrate this.).

Although the relation with previous developmental work in perseveration is clear, we would like to highlight that the behavior elicited in the current study is not, strictly speaking, perseveration. The A-not-B error, for instance, entails repeating what is essentially the same action. Here, participants cannot repeat the same exact action—they need to rotate slightly further each time. They can, however, repeat the same type of action (e.g., pronation). Immediate movement history changed the point at which participants were compelled to switch to a new behavior (e.g., from pronation to supination). As noted by Kelso et al. (1994), in dynamic terms, this more closely resembles *hysteresis*, the tendency of a system to persist in its current state longer than might be predicted from a consideration of the forces acting on it. Here, the force is the perceptual information about the efficiency of the movement that led to a transition from one action to another at a specific point in the random condition. Systematic rotation changed the task dynamic slightly and created a slight resistance to this transition. The point at which a person switches emerges from the task constraints.

Overall, the current data suggest that immediate movement history generates a bias in prehension action selection. Like all biases noted in the literature, immediate movement history helps reduce the space of potential actions to a manageable number size (specifically, to a version of the action just selected). This reflects the fact that any switch to a new movement has costs associated with it, even for skilled movers. The decision to switch emerges online when the costs are offset by the benefits that result from switching to a more efficient movement. Both skilled and unskilled reachers (adults and children) display this pattern, suggesting that immediate movement history is an important and widespread determinant of future action selection.

ACKNOWLEDGMENTS

This work was partly supported by grants from Scottish Enterprise, Action Medical Research, and the Wellcome Trust.

REFERENCES

Arbib, M. A. (1985). Schemas for the temporal organization of behaviour. *Human Neurobiology, 4,* 63–72.

Cohen, R. G., & Rosenbaum, D. A. (2004). Where grasps are made reveals how grasps are planned: Generation and recall of motor plans. *Experimental Brain Research, 157*, 486–495.

Cruse, H. (1986). Constraints for joint angle control of the human arm. *Biological Cybernetics, 54,* 125–132.

Cruse, H., Wischmeyer, E., Brüwer, M., Brockfeld, P., & Dress, A. (1990). On the cost functions for the control of the human arm movement. *Biological Cybernetics, 62,* 519–528.

de Lussanet, M. H. E., Smeets, J. B. J., & Brenner, E. (2001). The effect of expectations on hitting moving targets: Influence of the preceding target's speed. *Experimental Brain Research, 137,* 246–248.

de Lussanet, M. H. E., Smeets, J. B. J., & Brenner, E. (2002) The relation between task history and movement strategy. *Behavioral Brain Research, 129,* 51–59.

Dixon, P., Li, H., & Read, L. (2007, July). *Perseveration of grip aperture.* Paper presented at the Experimental Psychology Society Meeting, Edinburgh, United Kingdom. Retrieved August, 2007, from http://www.eps.ac.uk/meetings/Programme0707.pdf

Gibson J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum.

Jax, S. A., & Rosenbaum, D. A. (2007). Hand path priming in manual obstacle avoidance: Evidence that the dorsal stream does not only control visually guided actions in real time. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 425–441.

Joseph, R. (1999). Frontal lobe psychopathology: Mania, depression, confabulation, catatonia, perseveration, obsessive compulsions and schizophrenia. *Psychiatry, 62,* 138–172.

Kelso, J. A. S., Buchanan, J. J., & Murata, T. (1994). Multifunctionality and switching in the coordination dynamics of reaching and grasping*, Human Movement Science, 13,* 63–94.

Kuhtz-Buschbeck, J. P., Stolze, H., Johnk, K., Boczek-Funcke, A., & Illert, M. (1998). Development of prehension movements in children: A kinematic study. *Experimental Brain Research, 122,* 424–432.

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology, 41,* 365–378.

Mon-Williams, M., Tresilian, J. R., Bell, V. E., Coppard, V. L., Nixdorf, M., & Carson, R. G. (2005). The preparation of reach-to-grasp movements in adults, children, and children with movement problems. *Quarterly Journal of Experimental Psychology Section A, 58,* 1249–1263.

Rosenbaum, D. A., Heugten, C. V., & Caldwell, G. C. (1996). From cognition to biomechanics and back: The end state comfort effect and the middle-is-faster effect. *Acta Psychologica, 94,* 59–85.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Motor representation and control, Attention and Performance XIII* (pp. 321–342). Hillsdale, NJ: Erlbaum.

Rosenbaum D. A., Meulenbroek, R. G. J., & Vaughan, J. (1996). Three approaches to the degrees of freedom problem in reaching. In A. M. Wing, P. Haggard, & R. Flanagan (Eds.), *Hand and brain: Neurophysiology and psychology of hand movement* (pp. 169–185). San Diego: Academic Press.

Rosenbaum, D. A., Meulenbroek, R. G., Vaughan, J., & Jansen, C. (2001). Posture based planning: Applications to grasping. *Psychological Review, 108,* 709–734.

Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: Selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 18,* 1058–1073.

Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., & Stewart, E. (1993). Plans for object manipulation. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV—A silver jubilee: Synergies in experimental psychology, artificial intelligence and cognitive neuroscience* (pp. 803–820). Cambridge, MA: MIT Press, Bradford Books.

Rosenbaum, D. A., Weber, R. J., Hazelett, W. M., & Hindorff, V. (1986). The parameter remapping effect in human performance: Evidence from tongue twisters and finger fumblers. *Journal of Memory and Language, 25,* 710–725.

Scholz, J., & Kelso, J. (1990). Intentional switching between patterns of bimanual coordination depends on the intrinsic dynamics of the patterns. *Journal of Motor Behavior, 22,* 98–124.

Spencer, J. P., Smith, L. B., & Thelen, E. (2001). Tests of a dynamic systems account of the A-not-B error: The influence of prior experience on the spatial memory abilities of two-year-olds. *Child Development, 72,* 1327–1346.

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001) The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral & Brain Sciences, 24,* 1–34.

Tresilian, J. R., Mon-Williams, M., Coppard, V. L., & Carson, R. G. (2005). Developmental changes in the response to obstacles during prehension. *Journal of Motor Behavior, 37(2)*, 103–10.

van Bergen, E., van Swieten, L. M., Williams, J. H. G., & Mon-Williams, M. (2007). The effect of orientation on prehension movement time. *Experimental Brain Research, 178*, 180–193.

Van Der Wel, R. P., Fleckenstein, R., Jax, S., & Rosenbaum, D. A. (2007). Hand path priming in manual obstacle avoidance: Evidence for abstract spatio-temporal forms in human motor control. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 1117–1126.

Submitted September 4, 2007
Revised October 5, 2007
Second revision October 31, 2007