Measuring Prospective Motor Control in Action Development

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As accepted for publication in Journal of Motor Learning and Development,
 doi: 10.1123/jmld.2016-0078

Submitted: November 15, 2016

Accepted: May 09, 2017

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Abstract

This article critically reviews kinematic measures of prospective motor control. Prospective motor control, the ability to anticipatorily adjust movements with respect to task demands and action goals, is an important process involved in action planning. In manual object manipulation tasks, prospective motor control has been studied in various ways mainly using motion-tracking. For this matter, it is crucial to pinpoint the early part of the movement that purely reflects prospective (feed-forward) processes, but not feedback influences from the unfolding movement. One way of defining this period is to rely on a fixed time criterion; another is to base it flexibly on the inherent structure of each movement itself. Velocity – as one key characteristic of human movement – offers such a possibility and describes the structure of movements in a meaningful way. Here, I argue for the latter way of investigating prospective motor control by applying the measure of peak velocity of the first movement unit. I further discuss movement units and their significance in motor development of infants and contrast the introduced measure with other peak-velocity related measures and duration related measures.

(WORD COUNT: 181)

Keywords: motor control, movement unit, infancy, feed-forward, action planning, motor development

Introduction

To interact with our environment in a purposeful manner, our actions need to be prospective and take the constant change of the environment into consideration. Imagine in this context the challenge of catching a ball. One has to anticipate the future position of the flying ball while moving oneself to be able to catch it. Simply considering the current position of the ball would lead to miss the target, as the ball has moved further in the meantime. Another challenging fact is that feedback from one's own body and the ever-changing environment needs relatively long time to be processed. This sensorimotor delay is estimated to be around 100 milliseconds in adults (Jeannerod, 1988) and with 200 to 400 milliseconds even longer in infants (Berthier & Robin, 1998). Thus, actions have to be prospective to bridge this processing delay of the sensorimotor system (von Hofsten, 2014). In other words, one needs prospective motor control. Daily life actions, however, do often consist of more than just one action step. For instance, we reach for a cup, to either drink from it or to place it in a cupboard. Multiple-step actions, such as reaching for objects to manipulate them, are another action type, where prospective motor control is crucial for achieving goals (Gottwald et al., 2017).

This paper defines prospective motor control and discusses different ways of measuring it in adults, children and infants. In doing so, the focus is on kinematic measures of prospective motor control. Other related measures as anticipatory postural adjustments (e.g., Witherington et al., 2002), reaction time prior to movement initiation (e.g., Sidaway, 1991), or measures related to the *end-state-comfort effect* (Rosenbaum et al., 1990) are not considered. Finally, a method pinpointing prospective motor control in infancy by measuring the peak velocity of the first movement unit is introduced.

Prospective motor control as a feed-forward control process

Motor control describes the interaction between the brain and the (rest of the) body with the environment to create goal-directed movements (Latash, 2012). In other words, motor control is concerned with the tight action-perception couplings needed to produce meaningful actions, as described by the *dynamical systems theory* (Thelen, 1992; Thelen & Smith, 1994).

There are two basic processes that use sensorimotor information for motor control: Feed-forward and feedback control. Most human movements are controlled by both processes (Latash, 2012). Here we focus on the prospective process of feed-forward control. Prospective motor control is concerned with feed-forward control and can be described as the ability to control one's actions according to action goals and the changing environment in an *anticipatory* manner (Gottwald et al., 2017; Gottwald & Gredebäck, 2015). Thus, prospective motor control is a key component of action (von Hofsten, 1993).

Prospective motor control is of central importance for the developing infant already (von Hofsten, 1993) and infants' actions are partly prospective from early on (van der Meer, van der Weel, & Lee, 1995; von Hofsten, 1991, 2004; von Hofsten & Rönnqvist, 1993). Infants begin to prospectively control their reaches for example from the age of five months, as measured by time to contact between hand and object and the timing of hand closure (von Hofsten & Rönnqvist, 1988). At 8 months, infants are capable of catching an object moving with the speed of 120 cm/s and their involved reaches are prospectively controlled (von Hofsten, 1983). Infants' reaching movements develop from being less straight, continuous and organized in the beginning to more controlled and direct later in life (von Hofsten, 1991). At the age of 3 years, reaching kinematics resemble the ones of adults (Konczak & Dichgans, 1997). Adults' reaches are smoother and contain less sub-movements than infants' reaches (Jeannerod, 1988; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987; von Hofsten, 1993).

Movement units and prospective motor control. These sub-movements are called movement units and reflect a meaningful structure of human movements. Human movements usually contain several accelerations and decelerations in velocity; that is humans speed up and slow down while performing actions (von Hofsten, 1979, 1991). This results in the typical bell-shaped velocity pattern of human movements (Jeannerod, 1988), wherein each “bell” constitutes one movement unit lasting a few hundred milliseconds (for illustration of a velocity profile see e.g. Gottwald et al., 2017, p. 6).

According to von Hofsten, every movement unit is assumed to be planned in advance – in other words prospectively controlled – and can therefore reflect a feed-forward process. The movement trajectory within each movement unit is relatively straight and can be corrected within the subsequent movement unit. Especially the first movement unit is important for prospective motor control, because it reflects the initial motor plan without influences of feedback from the unfolding movement (von Hofsten, 1979; von Hofsten & Rönnqvist, 1993).[1] Through infancy the number of movement unit decreases and the length of the first movement relatively increases. In adults, highly prospectively controlled reaches usually consist of one movement unit (Jeannerod, 1988). This indicates that reaching becomes more prospectively controlled in the course of development (Cunha et al., 2015; Grönqvist, Strand Brodd, & von Hofsten, 2011; von Hofsten, 1993).

Measurements of prospective motor control

Prospective motor control has been measured basically in two different ways: By measuring the full movement duration (Table 1.1) or by relying on peak velocity of the movement (Table 1.2, 1.3, and 1.4). Peak-velocity related measures in turn can be subdivided into three categories. I will elaborate on the different measurements in the following paragraphs.

[1] Marteniuk et al. (1987) argue that the acceleration phase of a movement reflects feed-forward processes and the subsequent deceleration phase might be modified by feedback control processes. Consequently, only the first part (i.e. the acceleration phase) of the first movement unit would purely reflect the initial motor plan.

Full movement duration. The duration of full movements can be investigated in action sequences, as for example reaching for an object to place it somewhere else. If the action parameters of the first action (reaching) are kept constant but varied in the subsequent action step (placing), kinematic differences in the prior reaching duration should be related to the parameters of the subsequent action (as the action parameters of the reach itself stay invariant). Examples for the measure of full movement duration are two studies by Fabbri-Destro, Cattaneo, Boria, and Rizzolatti (2009), and Zaal and Thelen (2005). Fabbri-Destro et al. (2009) demonstrated that seven-year-old typical developing children reach significantly faster for an object when they subsequently place it into a large container rather than a small one. In other words, they control their reaches with respect to future task demands of the placing action. Zaal and Thelen (2005) showed that infants between seven and nine months of age reach faster for a large object than for a small object. Both studies used durations of the full movement as measure of prospective motor control. In accordance with Fitts' law (Fitts, 1954) it takes more time to perform a difficult action (reaching for a small object, placing an object into a small box) than to perform an easy action (reaching or a large object, placing an object into a large box). The more difficult action requires more precision than the easier action does. Taking the difficulty or precision demands of the subsequent action step into account while reaching indicates prospective motor control. However, there are issues with this approach. Movement performance is seldom relying on feed-forward processes only (as prospective motor control), but also on feedback processes from the current movement (Latash, 2012). Thus, feedback processes might influence the full movement duration. Consequently, if a movement comprises more than one movement unit, the duration of the full movement indexes the complex interplay of prospective motor control *and* feedback processes instead of indexing prospective motor control *only*. The reaches of infants often contain several movement units (von Hofsten, 1991), which let the measurement of full movement durations appear to be problematic in infancy studies.

Peak velocity. An approach handling these issues is to specifically look at the relevant parts of the movement. These relevant parts can be identified by investigating the velocity profile of the movement. As mentioned above, velocity is a key characteristic of goal-directed movements and peak velocity can inform about prospective motor control. There are three possibilities how peak velocity can index prospective motor control: First, analyzing the relative duration of the deceleration time, which is the time after the peak in velocity (Table 1.2). Second, using peak velocity of the full movement as an indicator of prospective motor control (Table 1.3). A third possibility focusing on the first movement unit will be introduced thereafter (Table 1.4).

First, concerning the duration of the deceleration phase of adult pointing and grasping movements, Marteniuk et al. (1987) demonstrated that deceleration durations are longer for actions that require more precision (i.e. actions that are more difficult). In this study, participants slowed down earlier in their movements towards goal objects that were small (vs. large), soft (vs. resilient) or that should be subsequently placed into a small box (vs. large box). These results were replicated and extended for different movement types in multiple-step actions by Armbrüster and Spijkers (2006) for adults.[2] Children between the ages of six and eleven years demonstrate prospective motor control based on the subsequent action as well, as Wilmut, Byrne, and Barnett (2013) showed. In their study, six- to eleven-year-old children had shorter relative deceleration durations when their reaches were followed by throwing as compared to placing actions. As this was not the case for four- to five-year-old children, Wilmut et al. (2013) argue that the ability to prospectively control reaching based on the subsequent action characteristics improves with age. Concerning an even younger age group, Chen, Keen, Rosander, and von Hofsten (2010) demonstrated that 18- to 21-month-olds' reaching actions have an earlier peak in velocity when the subsequent action requires

[2] However, Johnson-Frey, McCarty, & Keen (2004) did not find effects of precision demands of the following action on the prior reach in adults, but effects of action type and the overall goal of the multiple-step action (lifting, placing or manipulating) on the deceleration duration of the prior reach.

more precision. This means that the children started to decelerate their reaches earlier, when they were going to build a tower of blocks as when they were going to place a block into a container. This measure is however not the same as the measure of the relative amount of deceleration time (as used by Armbrüster & Spijkers, 2006; Marteniuk et al., 1987; Wilmut et al., 2013 for adults and older children) of a movement, as reaching at this early age might consist of more than one movement unit. Chen et al. (2010) do not report the number of movement units and do not relate their measurement to the number of movement units. It is therefore difficult to compare their measure with the measure of relative amount of deceleration time, as they might capture different parts of the movement.

Another possibility to address prospective motor control by peak velocity is, second, to directly measure peak velocity in multiple-step actions. In a study by Claxton, Keen, and McCarty (2003), 10-month-olds reached for an object and subsequently either threw it or placed this object. Claxton et al. (2003) found that the infants reached with a greater peak velocity when they subsequently threw the object as when they placed it. These authors found no difference in reaching duration or time of peak velocity between both multiple-step actions. Similarly, Mash (2007) found no difference in reaching duration but in peak velocity, when 9- to 15-month-olds reached for differently weighted objects to lift them.

One important difference between reaches in adults and older children and the reaches of infants is the number of movement units. As previously mentioned, infants' reaches are less mature and usually contain more than one movement unit, whereas older children's and adults' reaches are more skilled and consequently often consist of only one movement unit (Jeannerod, 1988; von Hofsten, 1991). This difference could explain the differences in the deceleration results in the mentioned research on adults and older children (Armbrüster & Spijkers, 2006; Marteniuk et al., 1987; Wilmut et al., 2013) and the research on infants (Chen et al., 2010; Claxton et al., 2003; Mash, 2007). When it comes to infants' less mature reaches, the occurrence of more than one movement unit – and the related feedback processes – has to be taken into account.

This occurrence of more than one movement unit, however, does not need to be of disadvantage, but can be also used to measure prospective motor control. Actually, prospective motor control can be measured by using the fact that movement units are planned one after another (von Hofsten, 1993). The first movement unit indexes prospective motor control, whereat different characteristics of the movement can be looked at. As a third possibility to use movement velocity as an indicator of prospective motor control, one infant study by Gottwald et al. (2017) using the first movement unit as a measurement of prospective motor control should be mentioned.

Gottwald et al., (2017) investigated whether 14-month-olds prospectively control their reaching actions based on the difficulty of future actions in multiple-step actions. The authors used a reach-to-place task, with difficulty of the placing action varied by goal size and goal distance. The infants reached for an object and subsequently placed it into a cylinder. The cylinder was placed either close to the object (easy action) or more away from the object (difficult action) and was large (easy action) or small (difficult action) of size. Infants' prior reaching movements were measured with a motion-tracking system and peak velocity of the first movement unit of the reach indicated prospective motor control. Results were that both difficulty aspects (distance and size) had an impact on prior reaching: The larger the goal size and the closer the distance to the goal, the faster infants were in the beginning of their reach towards the object. The authors interpreted this as a demonstration of prospective motor control for future actions in multiple-step actions.

This study (Gottwald et al., 2017) investigated prospective motor control based on the inherent structure of each movement itself. The following paragraph will briefly discuss this measure in contrast to duration- and deceleration-based measures of prospective motor control.

Discussion

The duration of a movement's deceleration phase relative to its total duration is an established measurement of prospective motor control for future actions in adults (Armbrüster & Spijkers, 2006; Johnson-Frey, McCarty, & Keen, 2004; Marteniuk et al., 1987). If reaching movements are mature and consist of one movement unit only, the relative deceleration duration indicates the consideration of the characteristics of the subsequent action. The mentioned studies demonstrated different lengths of deceleration durations for both different action types and for same action types differing in difficulty (respectively precision requirements). Spending more time decelerating when the subsequent action requires more precision is a characteristic of skilled reaching. During childhood, the relative deceleration duration generally increases with age (Wilmut et al., 2013), which can be interpreted as an indicator of the improving ability to prospectively control reaching actions with respect to future actions.

Marteniuk et al. (1987) argue that the main factor of interest is the point in time when peak velocity of a movement is reached relative to its full duration. The time of peak velocity and the relative length of the deceleration phase match each other, if the movement comprises only one movement unit, as it is the case for most adults' and skilled (older) children's reaches. Even though not reported, we can therefore assume that the reaches of the discussed adult and children studies (Armbrüster & Spijkers, 2006; Johnson-Frey et al., 2004; Marteniuk et al., 1987) contain only one movement unit. The depicted velocity curves in these articles are suggesting this as well.

However, the picture is less clear for prospective motor control in infancy, where the number of movement units per reach differs. Consequently, the reaches of infants can have several peaks in velocity (von Hofsten, 1991). The time of peak velocity of the complete reach does not have to be related to the relative length of the deceleration phase and there might be more than one deceleration phases. Von Hofsten (1993) discusses the development of prospectively controlled reaching from being less straight and controlled at reach onset to becoming more direct and mature in the course of infancy. Wilmut et al. (2013) studied prospective motor control later in childhood from four to eleven years of age, when reaching kinematics are adult-like (Konczak & Dichgans, 1997), and found the relative deceleration time to increase with age (across action types). Within the six to eleven age bracket, the relative length of the duration phase (e.g. time after peak velocity) was related to the characteristics of the subsequent action[3]. This was also found in infancy for the ages of 18 to 21 months by Chen et al. (2010), but not earlier in infancy for 10-month-olds (Claxton et al., 2003). These inconsistencies could be related to the number of movement units in less mature reaches in infancy.

Chen et al., (2010) expect the reaches of 18- to 21-months-olds to resemble the reaches of adults and consequently interpret their measure of the time of peak velocity as equivalent to the measure of relative length of the deceleration phase in older children and adults. Given that the number of movement units of reaches within this age bracket is still higher than in older age groups (Konczak & Dichgans, 1997), this assumption appears disputable. How much of the reaching time after the peak in velocity is dedicated to deceleration? How many movement units are following this peak? Chen et al. (2010) do not report movement units, so that these questions remain unanswered. However, they found an earlier peak in velocity, when the subsequent action required more precision (vs. less precision), which relates to the results of studies in adults (Armbrüster & Spijkers, 2006; Johnson-Frey et al., 2004; Marteniuk et al., 1987) and older children (Wilmut et al., 2013). The finding that in infants older than seven months, the first movement unit mostly is the largest unit of the movement, characterized by the highest peak in velocity and the longest duration (von Hofsten, 1993), additionally supports the measure by Chen et al. (2010). They

[3] In contrast, the group of the four- to five-year-olds did not significantly differ in their relative deceleration duration for the different action types.

might have addressed the first movement unit by using the time of peak velocity of the full reach. Most likely, the highest peak is within the first movement unit.

The work with 14-month-olds by Gottwald et al. (2017) addresses these issues by focusing on the first part of the movement that is not influenced by feedback processes – the first movement unit. These authors additionally measured full movement durations and found less effects of the subsequent action on the full movement than on the first movement unit. I would like to argue that the measure of peak velocity of the first movement unit is more sensitive than the measure of movement duration. This would be in line with Claxton et al. (2003), who found no effects on full movement duration, but on peak velocity.

Measures of movement duration and velocity are of course related – faster reaches take less time than slower reaches. But the first part of an infant’s reach might be especially informative about feed-forward processes in motor control (as prospective motor control). Pure measures of movement duration could possibly hide these processes in infancy.

The question, what measurements to use – deceleration duration or peak velocity of the first movement unit – depends also on the precise research question. If prospective motor control of the current action (step), as for example catching or reaching for a ball, is of interest, peak velocity of the first movement unit should be measured. The peak velocity of the first movement unit indexes feed-forward processes without the influence of feedback processes, irrespective of the question, if the full first movement unit is planned in advance (as von Hofsten, 1991, 1993, argues) or if the deceleration part of the first movement unit is already shaped by feedback processes (as Marteniuk et al., 1987, suggest). If motor planning of the subsequent action step in multiple-step actions, such as reaching for a cup to place it somewhere else, is of interest, both measurements could be applied. Deceleration duration of the full movement can index planning of the next action step, irrespective of the actual number of movement units, as Chen et al. (2010) demonstrated. It is of theoretical interest, if their measure reflects prospective motor control or the complex interplay of prospective motor control and feedback processes. The discussed study by Gottwald et al. (2017) in contrast purely addresses prospective motor control without the influences of feedback from the unfolding movement. In this case, we can certainly talk about prospective motor control.

Future studies should address these questions further by comparing peak velocity of the first movement unit, peak velocity of the full movement and the relative deceleration duration in infant's single actions and multiple-step actions. At the same time, the number of movement units should be reported. Such studies could improve our understanding about the interplay of feed-forward and feedback processes and thus on the interrelation between motor control and motor planning.

Conclusion

This paper defined prospective motor control and discussed different ways of measuring it in action development from infancy to adulthood. The measurement of peak velocity of the first movement unit (covering the first 200 to 600 milliseconds of an infant's reach) was described as a measurement of prospective motor control in infancy. This measurement is based on the characteristics of the movement itself and allows studying feed-forward processes in motor control in infancy.

Conflict of interest

The author declared that she had no conflicts of interest with respect to her authorship or the publication of this article.

References

Armbrüster, C., & Spijkers, W. (2006). Movement planning in prehension: do intended actions influence the initial reach and grasp movement? *Motor Control*, *10*(4), 311–329.

Berthier, N. E., & Robin, D. J. (1998). Midreach correction in 7-month-olds. *Journal of Motor Behavior*, *30*(4), 290–300. https://doi.org/10.1080/00222899809601345

Chen, Y., Keen, R., Rosander, K., & von Hofsten, C. (2010). Movement Planning Reflects Skill Level and Age Changes in Toddlers. *Child Development*, *81*(6), 1846–1858. https://doi.org/10.1111/j.1467-8624.2010.01514.x

Claxton, L. J., Keen, R., & McCarty, M. E. (2003). Evidence of motor planning in infant reaching behavior. *Psychological Science*, *14*(4), 354–356.

Cunha, A. B., Soares, D. de A., Carvalho, R. de P., Rosander, K., von Hofsten, C., & Tudella, E. (2015). Maturational and situational determinants of reaching at its onset. *Infant Behavior and Development*, *41*, 64–72. https://doi.org/10.1016/j.infbeh.2015.06.003

Fabbri-Destro, M., Cattaneo, L., Boria, S., & Rizzolatti, G. (2009). Planning actions in autism. *Experimental Brain Research*, *192*(3), 521–525. https://doi.org/10.1007/s00221-008-1578-3

Fitts, P. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47*, 381–391.

Gottwald, J. M., De Bortoli Vizioli, A., Lindskog, M., Nyström, P., Ekberg, T. L., von Hofsten, C., & Gredebäck, G. (2017). Infants prospectively control reaching based on the difficulty of future actions: To what extent can infants' multiple-step actions be explained by Fitts' law? *Developmental Psychology*, *1*(53), 4–12. https://doi.org/http://dx.doi.org/10.1037/dev0000212

Gottwald, J. M., & Gredebäck, G. (2015). Infants' prospective control during object manipulation in an uncertain environment. *Experimental Brain Research*, *233*(8), 2383–2390. https://doi.org/10.1007/s00221-015-4308-7

Grönqvist, H., Strand Brodd, K., & von Hofsten, C. (2011). Reaching strategies of very preterm infants at 8 months corrected age. *Experimental Brain Research*, *209*(2), 225–233. https://doi.org/10.1007/s00221-011-2538-x

Jeannerod, M. (1988). *The neural and behavioural organization of goal-directed movements.* New York, NY, US: Clarendon Press/Oxford University Press.

Johnson-Frey, S. H., McCarty, M., & Keen, R. (2004). Reaching beyond spatial perception: Effects of intended future actions on visually guided prehension. *Visual Cognition*, *11*(2–3), 371–399. https://doi.org/10.1080/13506280344000329

Konczak, J., & Dichgans, J. (1997). The development toward stereotypic arm kinematics during reaching in the first 3 years of life. *Experimental Brain Research*, *117*(2), 346–354. https://doi.org/10.1007/s002210050228

Latash, M. L. (2012). *Fundamentals of Motor Control* (1st ed.). London: Academic Press.

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology*, *41*(3), 365–378. https://doi.org/10.1037/h0084157

Mash, C. (2007). Object representation in infants’ coordination of manipulative force. *Infancy*, *12*(3), 329–341. https://doi.org/10.1111/j.1532-7078.2007.tb00246.x

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: overhand versus underhand grip. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 321–342). Hillsdale: Lawrence Erlbaum Associates.

Sidaway, B. (1991). Motor programming as a function of constraints on movement initiation. *Journal of Motor Behavior*, *23*(2), 120–30. https://doi.org/10.1080/00222895.1991.9942029

Thelen, E. (1992). Development as a dynamic system. *Current Directions in Psychological Science*, *1*(6), 189–193. https://doi.org/10.1016/S1364-6613(03)00156-6

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

van der Meer, A. L., van der Weel, F. R., & Lee, D. N. (1995). The functional significance of arm movements in neonates. *Science (New York, N.Y.)*, *267*(5198), 693–695. https://doi.org/10.1126/science.7839147

von Hofsten, C. (1979). Development of visually directed reaching: The approach phase. *Journal of Human Movement Studies*, (5), 160–178.

von Hofsten, C. (1983). Catching skills in infancy. *Journal of Experimental Psychology: Human Perception and Performance*, *9*(1), 75–85. https://doi.org/10.1037/0096-1523.9.1.75

von Hofsten, C. (1991). Structuring of early reaching movements: A longitudinal study.pdf. *Journal of Motor Behavior*, *23*(4), 280–292.

von Hofsten, C. (1993). Prospective control: A basic aspect of action development. *Human Development*, *36*, 253–270.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences*, *8*(6), 266–272. https://doi.org/10.1016/j.tics.2004.04.002

von Hofsten, C. (2014). Predictive actions. *Ecological Psychology*, *26*(1–2), 79–87. https://doi.org/10.1080/10407413.2014.874902

von Hofsten, C., & Rönnqvist, L. (1988). Preparation for grasping an object: a developmental study. *Journal of Experimental Psychology. Human Perception and Performance*, *14*(4), 610–621. https://doi.org/10.1037/0096-1523.14.4.610

von Hofsten, C., & Rönnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development*, *64*(4), 1046–1057. https://doi.org/10.1111/j.1467-8624.1993.tb04187.x

Wilmut, K., Byrne, M., & Barnett, A. L. (2013). To throw or to place: Does onward intention affect how a child reaches for an object? *Experimental Brain Research*, *226*(3), 421–429. https://doi.org/10.1007/s00221-013-3453-0

Witherington, D. C., Hofsten, C., Rosander, K., Robinette, A., Woollacott, M. H., & Bertenthal, B. I. (2002). The development of anticipatory postural adjustments in infancy. *Infancy*, *3*(4), 495–517. https://doi.org/10.1207/S15327078IN0304_05

Zaal, F. T. J. M., & Thelen, E. (2005). The developmental roots of the speed-accuracy trade-off. *Journal of Experimental Psychology. Human Perception and Performance*, *31*(6), 1266–1273. https://doi.org/10.1037/0096-1523.31.6.1266

Table 1. Studies on prospective motor control

Measure	Authors	Participants	Task	Results
1. Full movement duration	Fabbri-Destro et al. (2009)	10-year-old children (and 7-year-olds with ASD)	Reach-to-place actions involving two different goal sizes	The typical children reached faster, when the subsequent action involved the large goal (vs. small goal), whereas the ASD-children did not.
	Zaal & Thelen (2005)	7- to 11-month-old infants	Reach-to-grasp small and large objects.	Reaching time was shorter for the large object than for the small object.
2. Deceleration duration (time of peak velocity relative to movement duration)	Marteniuk et al. (1987)	Adults (university students)	Pointing and grasping	Earlier peak velocity, i.e. longer deceleration phase, and lower peak velocity for difficult movements (vs. easy movements).
	Armbrüster & Spijkers (2006)	Adults (18 – 40 years of age)	Reach-to-grasp, reach-to-throw and reach-to-place actions	Earlier peak velocity in reaching, i.e. longer deceleration phase, when the following movement was more difficult (vs. easy).
	Johnson-Frey et al. (2004)	Adults (university students)	Reach-to-place, reach-to-lift and reach-to-manipulate actions	Overall reaching duration and deceleration time were shorter, when the object was subsequently transported (vs. lifted or manipulated).
	Wilmut et al. (2013)	4- to 11-year-old children	Reach-to-place and reach-to-throw sequences involving two goal sizes	Reaching duration and relative deceleration times were shorter, when followed by throwing (vs. placing).
	Chen et al. (2010)	18- to 21-month-old toddlers	Reach-to-place task (imprecise task) reach-to-pile task (precise).	Earlier peak velocity, when the subsequent action was precise (vs. imprecise). Reaching distance was longer for the imprecise task (placing blocks in container) than for the precise task (piling blocks). Reaching duration was longer, when the subsequent action was imprecise (vs. precise).
3. Peak velocity of the full movement	Claxton et al. (2003)	10-month-old infants	Reach-to-place and reach-to-throw actions	Peak velocity of the reach was higher, when the subsequent action throwing (vs. placing). No differences found in reaching duration and deceleration time for placing vs. throwing.
	Mash (2007)	9- to 15-month-old infants	Reaching, and lifting of heavy and light objects with color information on object weight.	Reaching: Higher peak velocity for (expected) heavy object (vs. expected light object). No differences in reaching duration for the different objects. Lifting: Higher average velocity for unexpectedly light objects than expectedly light objects.
4. Peak velocity of the first movement unit	Gottwald et al. (2017)	14-month-old infants	Reach-to-place actions involving two goal sizes and two goal distances (action difficulty)	Peak velocity of the first movement unit was higher, when the subsequent movement was easy (large goal size, small goal distance) as compared to difficult (small goal size, large goal distance). Reaching duration was longer, when the subsequent action involved a longer distance (vs. shorter distance).