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Infants Prospectively Control Reaching Based on the Difficulty of Future Actions: To What Extent Can Infants' Multiple-Step Actions Be Explained by Fitts' Law?

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Prospective motor control, a key element of action planning, is the ability to adjust one's actions with respect to task demands and action goals in an anticipatory manner. The current study investigates whether 14-month-olds can prospectively control their reaching actions based on the difficulty of the subsequent action. We used a reach-to-place task, with difficulty of the placing action varied by goal size and goal distance. To target prospective motor control, we determined the kinematics of the prior reaching movements using a motion-tracking system. Peak velocity of the first movement unit of the reach served as indicator for prospective motor control. Both difficulty aspects (goal size and goal distance) affected prior reaching, suggesting that both these aspects of the subsequent action have an impact on the prior action. The smaller the goal size and the longer the distance to the goal, the slower infants were in the beginning of their reach toward the object. Additionally, we modeled movement times of both reaching and placing actions using a formulation of Fitts' law (as in heading). The model was significant for placement and reaching movement times. These findings suggest that 14-month-olds can plan their future actions and prospectively control their related movements with respect to future task difficulties.

Keywords: prospective motor control, action planning, action development, movement unit

A successful interaction with the environment requires that one plans ahead and adjusts the current action with respect to future task demands (von Hofsten, 2004). A person reaches differently for a small cup of espresso than for a big cup of coffee. Although the intention is the same, the movements required to execute the action vary in speed, precision, and force (cf. Hamilton & Grafton, 2007). What adults aim to do with an object once they have retrieved it is already evident in the kinematics of the reach toward it (Armbrüster & Spijkers, 2006; Hesse & Deubel, 2010; Johnson-Frey, McCarty, & Keen, 2004; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987).

Similar results can be observed in infancy and childhood. Fabbri-Destro, Cattaneo, Boria, and Rizzolatti (2009) showed that 7-year-olds reached significantly faster for an object when they subsequently placed it in a large container rather than a small one. Similar results have been obtained with children ages 4–11 (Wilmut, Byrne, & Barnett, 2013a, 2013b). Regarding earlier development, Claxton, Keen, and McCarty (2003) found that 10-month-old infants are already able to plan multistep actions in a prospective manner. When reaching for an object with the intent to throw it, infants were faster than when reaching with the intent to place the same object. Chen, Keen, Rosander, and von Hofsten (2010) demonstrated similar effects in 18- to 21-month-olds who were asked to use blocks to either build a tower or throw them in a basket.

These studies demonstrate that multistep action planning is an intrinsic part of individuals' actions and, further, that it develops

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Table 1 and Figures 1–4 are adapted versions of the table and figures appearing in the first author's dissertation.

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All procedures performed in studies involving human participants were in accordance with the ethical standards of the regional ethics committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the parents of all individual participants included in the study.

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early in life. This ability to prospectively control actions is critical to achieving the smooth completion of action sequences and is paramount for most forms of interaction with the world. In early infancy, this becomes particularly important for locomotion, object exploration, and imitation. At the age of 18 months, prospective motor control is related to executive function development (Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016). Later in life, it is a requirement for most actions, ranging from cooking dinner to driving a car and playing sports.

Actions can be understood as organized on different hierarchical levels, as for example, on the level of goals and intentions (e.g., drinking coffee) or on the level of kinematics (e.g., reaching for cups; Hamilton & Grafton, 2007). It is unclear at which action level children can use prospective motor control early in development. It is possible that infants plan differently for different types (or categories) of actions and goal intentions (e.g., reaching with the intent to throw vs. place an object, here referred to as *action type* planning). Possibly, infants are also able to plan their actions on a finer grained level, based on a continuous scale of task difficulty (here referred to as *action difficulty* planning). It is known from prior work with older children (Fabbri-Destro et al., 2009) that planning based on action difficulty is possible. This relation is described by Fitts' law (Fitts, 1954; for a review, see Plamondon & Alimi, 1997), which states that the movement time (MT) required to rapidly move to a target area is a function of the distance (D) to the target and the size (S) of the target given by $\mathrm{MT} = a + b \times \log_2(2\ \mathrm{D/S})$, where $\log_2(2\ \mathrm{D/S})$ is the spatial relative error or the index of difficulty[1] and a and b are empirical constants. In other words: The easier an action becomes, the less time it takes to successfully perform it. This leaves two possibilities for how action difficulty can be considered in prospective motor control: First, infants could use a simple heuristic to assess task difficulty, such as either goal size or goal distance. Another option is that infants rely on a combination of both goal size and goal distance, as described by Fitts' law.

In prior studies, the two levels (action type and action difficulty) in the action hierarchy have been confounded (because careful placing actions involve a different difficulty level than does throwing; Armbrüster & Spijkers, 2006; Marteniuk et al., 1987). The current study investigates prospective motor control by looking at two-step actions requiring infants to reach for a toy and place it in a cylinder. The fact that all actions belong to the same category (placing actions) but vary in terms of difficulty (distance to goal and size of goal) allowed us to assess the degree to which multistep action planning can be modulated to action difficulty, while still controlling for variations in action type. Participants in the study were 14 months of age, with the motor abilities required to control action sequences (cf. Verschoor, Paulus, Spapé, Biro, & Hommel, 2015) and an interest to participate in the current experimental task requiring reach-to-place actions.

The aim of the current study was twofold. First, we investigated whether prospective motor control in the beginning of the reach is based on the difficulty of the subsequent placing action (study of the kinematics). Peak velocity of the first movement unit (Gottwald & Gredebäck, 2015; von Hofsten, 1991) served as a measure for prospective motor control (von Hofsten, 1993). Second, we modeled movement times of both reaching and placing actions to determine whether infants' movements in action sequences can be described by Fitts' law and whether both difficulty aspects are involved (modeling Fitts' law). Each of these aims are elaborated in the following two sections.

Study of the Kinematics (Movement Velocity)

To precisely measure prospective motor control, we investigated the kinematics of the movements with a motion-tracking system (Qualisys, 2015; Gothenburg, Sweden, Qualisys Track Manager Version 2.12). Velocity is of central importance for movement control (Plamondon & Alimi, 1997). Specifically, the peak velocity of the first movement unit (the first acceleration and deceleration phase of the action) is of particular interest in evaluating prospective motor control revealing the initial motor plan (Gottwald & Gredebäck, 2015; von Hofsten, 1993; see Figure 1), before possible online feedback processes influence the movement (Jeannerod, 1988). In adults, simple reaching or pointing actions typically incorporate a large initial movement unit followed by some small adjustments toward the end of the movement (cf. Crossman & Goodeve, 1983; Jeannerod, 1988; Marteniuk et al., 1987). In comparison, infants use more movement units for the same actions. With maturation, the number of movement units decreases, indicating that reaches become more straight and precise, with fewer online corrections during the movement (von Hofsten, 1991). In the current study, we assess prospective motor control (Gottwald & Gredebäck, 2015) with the peak velocity of the first movement unit during reaching and relate this measure to the difficulty of the subsequent placement action. We hypothesized that infants plan their multistep actions at the level of action difficulty and, accordingly, would reach faster for the object when the subsequent placement action is easy rather than difficult (Hypothesis 1). In addition, we expected that goal size *and* goal distance would influence the perceived difficulty of the placement action, as formulated by Fitts' law (Hypothesis 2). If correct, this should be expressed by two significant main effects of goal size and goal distance or a significant interaction of goal size and goal distance on peak velocity of the first movement unit. If no significant effects are observed, it may be that action planning is restricted to different action types (throwing vs. placing) and is not sensitive to general task difficulty.

Modeling Fitts' Law (Movement Duration)

We additionally investigated to what degree the specific effects of goal size and goal distance influence infants' multistep action planning. To do so, we focused on movement times or durations of the reach and place actions involved in the task as the dependent variable. The reason for this is that the formal computational model focuses on this variable (Fitts, 1954; Welford, Norris, & Shock, 1969). We modeled movement time separately for the reaching and placement movements using a formulation of Fitts' law that allows for evaluating the separate contributions of goal size and goal distance (Welford et al., 1969). In this formulation, movement time (MT) is given by $\mathrm{MT} = a + b_{\mathrm{D}} \times \log_2(\mathrm{D}) + b_{\mathrm{S}} \times$

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[1] The index of difficulty (ID) relates to the different goal size and goal distance conditions in the present study, such that every different combination has a different ID value (see the Data Analysis section for details).

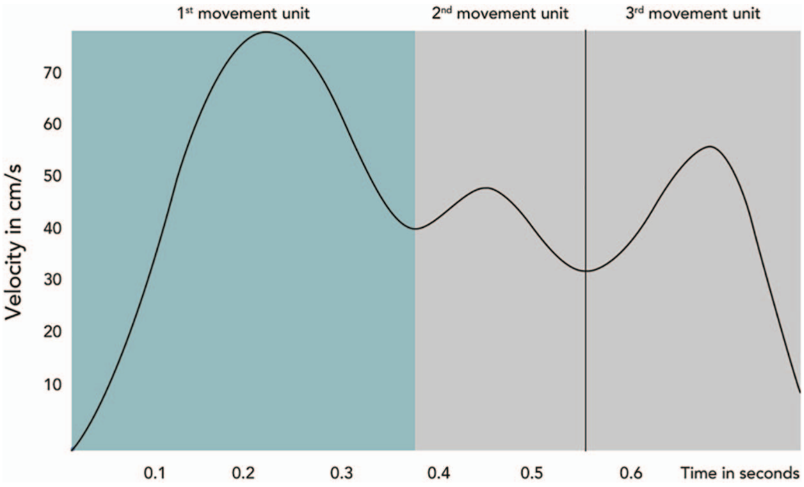

Figure 1. Velocity profile of one typical reach of a 14-month-old in this study. Movement units contain one acceleration and one deceleration phase. The first movement unit is marked in darker gray (blue in the online version). The vertical line indicates the border between second and third movement units. In the current example, the value of interest is around 220 ms: peak velocity of the first movement unit. Figure adapted from *Infants in Control: Prospective Motor Control and Executive Functions in Action Development* (p. 54), by Gottwald, 2016. See the online article for the color version of this figure.

$\log_2(1/S)$.[2] The model predicts that MT should increase when the action becomes more difficult. This should be most clearly expressed during the placement action—here we expected that Fitts' law could account for a substantial amount of variance in MT as a function of action difficulty. To our knowledge, only one previous study explicitly investigated whether infants' actions are well described by Fitts' law. Zaal and Thelen (2005) showed that 7- to 11-month-old infants reach slower for smaller objects than for larger. By regressing movement time on goal size, the authors could predict 45% of the variation in movement times. Further, without explicitly testing Fitts' law, Vishton, Ware, and Badger (2005) provided additional support that 8- and 9-months-olds reach consistently with Fitts' law. However, unlike the current study, Zaal and Thelen (2005) and Vishton et al. (2005) manipulated only goal size, not goal distance.

Additionally, our design allows for the evaluation of Fitts' law during multistep actions, rather than simple reach-to-grasp action as in prior studies (e.g., Zaal & Thelen, 2005). During the reaching action, all external aspects of the action were held constant. Infants always reached for the same object (maintaining goal size), which was always placed at a fixed and constant distance from the starting position of the hand (maintaining goal distance). Thus, any differences in movement times for this reaching action should likely be due to the difficulty of the subsequent placement action. Third, we expected movement times of both reaching and placing actions to be described by Fitts' law. Accordingly, the variation in duration would be explained by task difficulty (Hypothesis 3).

Method

Participants

The final sample included thirty-seven 14-month-old infants ($M_{\text{age}} = 427$ days, $SD = 9.40$, 16 female), randomly assigned to one of two conditions: *short distance condition* ($M_{\text{age}} = 413$ days, $SD = 12.35$, $n = 20$) and *long distance condition* ($M_{\text{age}} = 416$ days, $SD = 4.51$, $n = 17$). An additional 19 infants were tested but excluded from analysis due to unwillingness to perform the task ($n = 5$) or lack of compliance with inclusion criteria (i.e., they performed less than three valid trials per goal size; $n = 14$). Ninety-five percent of the sample ($n = 35$, $M_{\text{age}} = 415$ days, $SD = 9.40$, 14 female) was included for the movement analysis (see the Data Analysis and Results sections for details). Informed consent was obtained from the parents of all individual participants included in the study. Participants were recruited from the lab's database of parents who expressed interest in participating in research studies with their child. For participation, parents received a gift voucher of 100 Swedish crowns (US$11).

Materials

The object consisted of a plush toy orange (4.5 cm in diameter, 4 g in weight) with an attached visible marker for motion tracking. Goal locations were indicated by two Plexiglas cylinders wrapped in red felt fabric. The cylinders were both 16 cm in height and had inner diameters of either 12.3 or 5.3 cm (big and small cylinders, respectively; see Figure 2).

Procedure

After filling out a consent form, caregivers sat at a table with their infant on their lap, facing the experimenter. First, the exper-

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[2] Note that this expression is mathematically similar to the original formulation of Fitts' law because $b_D \times \log_2(D) + b_S \times \log_2(1/S) = c \times \log_2(D/S)$, where c is a constant. Thus, the two versions give similar predictions with respect to MT, but the Welford et al. (1969) version allows for an evaluation of the unique contributions of distance and size.

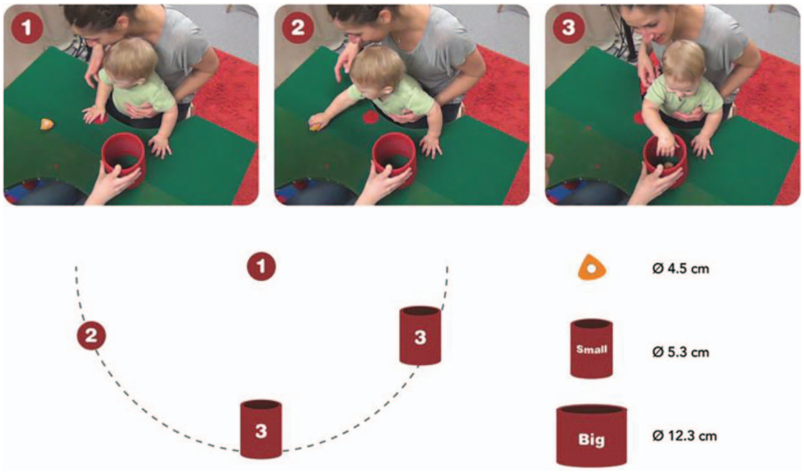

Figure 2. The experimental task consisted of placing the hand in a marked area (1), reaching for the object (2), and placing it in a cylinder (3). All participants placed an object (4.5 cm in diameter) in a small cylinder (5.3 cm in diameter) and a big cylinder (12.3 cm in diameter; within-subject variable goal size), whereas the cylinders were positioned in either a short distance (17 cm) or long distance (34 cm) from the pickup area (between-subjects variable goal distance). The positions of the object (2) and the cylinders (3) were on a half-circle around the infant defined by the reaching space of the right hand (1). The authors received signed consent for the individuals' likeness to be published in this article. Figure adapted from *Infants in Control: Prospective Motor Control and Executive Functions in Action Development* (p. 47), by Gottwald, 2016. See the online article for the color version of this figure.

imenter showed the object and one of the cylinders to caregiver and child. Then she placed the object and cylinder on defined positions on the table by saying, "Look, the orange! Can you place it in the cylinder?" The object and cylinders were placed in a half-circle around the infant (see Figure 2). The caregiver subsequently reached for the object and placed it in the cylinder with demonstrative joy. This was done twice to show the action to the infant.

The experimental task was inspired by prior research from Rosander and von Hofsten (2011). The experimenter presented the child with the object and, depending on experimental condition, either the small or the big cylinder. She then placed both objects on the table. The distance between the cylinder and the object varied depending on experimental condition and was either 17 cm (short distance condition) or 34 cm (long distance condition). Presentation order of the cylinders and their distance to the object were counterbalanced between subjects. Caregivers were instructed to hold the right arm of the infant from behind so that their right hand was on the starting area marked by a colored circle 5 cm in diameter. They released the arm when the experimenter indicated a new trial by saying, "Again." The infant was verbally encouraged to place the object in the cylinder, and both experimenter and caregiver praised the infant after the child performed the action. This was done for a maximum of 48 trials (two blocks of 2 [goal size: small or large] × 12 trials). Each block included six trials of one goal size and 12 trials of the other size, followed by six trials of the first size, with initial goal size counterbalanced across participants. This order was chosen to have as many repetitions in a row as possible, consistent with the procedure in prior studies on Fitts' law.

Data Recording

Data were recorded with a motion-tracking device (Qualisys Motion Capture Systems, Gothenburg, Sweden) at a sampling rate of 240 Hz. An eight-camera motion capture system was used to identify and track the motion of the reflective markers (.6 cm in diameter) attached to the infants' hands and the object. Additionally, the session was filmed by a video camera from a bird's-eye view.

Data Analysis

Videos were coded for the beginning and end of the two actions (reaching and placing) using Qualisys Track Manager (Qualisys, Gothenburg, Sweden). We identified the last frame before the start of the movement of the right hand, the first contact between hand and object, and the last frame before letting the object go to place it in the cylinder. Motion data of the right hand were analyzed (left reaches occurred rarely; i.e., at one trial each for four participants). Valid trials were limited to direct reaching movements without parental interference and moving from the marked area to the object, followed by direct placement movements. Valid placement movements included both successful and failed placements of the object, given that placing intention did not differ between these actions. An average of 10% (small goal size: 9%, big goal size: 11%) of the included reaching trials were followed by misses. Infants who accomplished at least half of the first block (12 trials) and contributed usable data for at least three valid trials per goal size were included in the analysis.

Motion capture data were used to extract the peak velocity of the first movement unit of the reaching action. A movement unit is defined based on the bell-shaped velocity profiles of the related movement and contains one acceleration and one deceleration phase (Gottwald & Gredebäck, 2015; von Hofsten, 1991). The peak velocity is reached at the end of the acceleration phase before deceleration. Motion-tracking position data were polynomially interpolated using Qualisys Track Manager (criterion: maximal gap of 30 frames) before exporting it to TimeStudio (http://timestudioproject.com; Nyström, Falck-Ytter, & Gredebäck, 2016), a free scientific workflow tool implemented in MATLAB allowing plug-in-based motion analysis in a customized manner. The data analysis program, including settings and source code, can be downloaded from uwid ts-c2c-355 within the TimeStudio environment. Consistent with prior research by Grönqvist, Strand Brodd, and von Hofsten (2011), data were filtered separately for *x*-, *y*-, and *z* coordinates with a three-sample-median filter to remove outliers. A Butterworth-low-pass filter at 10 Hz was applied on position data. Subsequently, three-dimensional velocity was calculated and also smoothed by using the Butterworth-low-pass filter at 10 Hz. Movement units were semiautomatically detected using the following criteria: a minimal movement unit peak distance of one sample and a movement unit merge threshold of eight samples.[3] Only trials that yielded valid motion data in more than 50% of the time of the trial were included. Further trials were excluded after visual inspection if the first movement unit was incomplete or if the full trial was visually noisy.

Peak velocity of the first movement unit was determined, and average peak velocities related to both goal sizes were calculated for every participant, resulting in two values per participant. A 2 × 2 mixed-design analysis of variance (ANOVA) with goal size (within-subject variable) and goal distance (between-subjects variable) as independent variables and peak velocity of the first movement unit as dependent variable was conducted to test Hypotheses 1 and 2.

Durations of the full reaching and placing movements were inferred from the video coding. The two mentioned versions of Fitts' law (Fitts, 1954; Welford et al., 1969) are essentially linear models. We therefore fitted the model that allows for evaluating the separate contribution of both goal size and goal distance using linear regression on group level data for the placement and reaching movement durations separately.[4] The index of difficulty related as follows to the conditions (distance [short, long] and goal size [small, big]): short–big, .47; long–big, 1.47; short–small, 1.68; and long–small, 2.68.

Results

Infants in the sample ($n = 37$) performed 28 trials (100%) on average, and 15 of them were judged as valid in the video coding (53%). Trials were excluded due to the following reasons (average percentages): The reaching movement did not start from the marked area (28%), no direct reaching (7%), no direct placing (7%), parental interference (2%), left hand reach (1%), or other action (2%). Because the motion-tracking data quality was low for two participants, the sample for the velocity analysis had a smaller size ($n = 35$). After visual inspection of the motion-tracking data, we excluded further trials due to these reasons: less than 50% data (9%), an incomplete first movement unit (6%), or noisiness (3%). On average, infants included in the movement velocity sample ($n = 35$) contributed usable data for 12 trials (43% of all performed trials).

Movement Velocity During Reaching

There was both a significant main effect of goal size, $F(1, 33) = 4.64$, $p = .039$, $\eta^2 = .12$, and a significant main effect of goal distance, $F(1, 33) = 11.18$, $p = .002$, $\eta^2 = .25$, on peak velocity of the first movement unit. No interaction between these two variables was detected, $F(1, 33) = 1.73$, $p = .198$, $\eta^2 = .05$. The smaller the goal size and the longer the distance to the goal, the slower the infants were in the beginning of the reach toward the to-be placed object (see Figure 3).

Placement Movement Duration

On average, the duration of the placing action (movement times) was 1.76 s (small goal size: $M = 2.27$ s, $SD = .70$; big goal size: $M = 1.24$ s, $SD = .48$; short goal distance: $M = 1.58$ s, $SD = .50$; long goal distance: $M = 1.97$ s, $SD = .46$; see Figure 4). For the placement action, the model was a good fit to the data ($R^2 = .476$, $p < .001$) and Fitts' law explained approximately 48% of the variation in the movement durations. Both goal size and goal distance were significant predictors (both ps $< .05$) in the model (see Table 1).[5]

Reaching Movement Duration

On average, the reaching duration equaled .87 s (small goal size: $M = .87$ s, $SD = .15$; big goal size: $M = .87$ s, $SD = .24$; short goal distance: $M = .82$ s, $SD = .14$; long goal distance: $M = .93$ s, $SD = .18$; see Figure 5). For the reaching action, where the difficulty of the task was constant, the model was significant ($R^2 = .056$, $p = .049$) and Fitts' law explained approximately 6% of the variation in movement duration. Although goal distance was a significant predictor in the model ($p = .02$), goal size was not (see Table 1).[6]

Discussion

In two separate analyses we could show that infants exhibit early action planning in action sequences. From the beginning of their movements, 14-month-olds reach faster for objects when their subsequent action is easy compared to difficult. The durations

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[3] The minimal peak distance defines the minimally needed distance between two maxima in velocity. A value of one sample means that two neighboring peaks must be at least 4.18 ms away from each other to define two separate movement units (in the case of a sampling rate of 240 Hz). The merge threshold is a critical value for the decision if two neighbored peaks in velocity should be merged into one movement unit. A value of eight samples means that peaks are merged into one movement unit if they are closer in time than 33.34 ms. Movement units would be merged in this case, assuming that the observed changes in velocity were rather due to insignificant or random changes in velocity than to meaningful characteristics of the infant's arm movements.

[4] The same results were obtained using a nonlinear least-squares approach to the model fitting.

[5] An ANOVA yielded similar results: significant main effect of goal distance, $F(1, 35) = 6.09$, $p = .019$, $\eta^2 = .15$; significant main effect of goal size, $F(1, 35) = 109.30$, $p < .001$, $\eta^2 < .76$; no significant interaction effect, $F(1, 35) = 2.46$, $p = .126$, $\eta^2 = .07$.

[6] An ANOVA yielded similar results: significant main effect of goal distance, $F(1, 35) = 4.55$, $p = .040$, $\eta^2 = .12$; no significant main effect of goal size, $F(1, 35) = .01$, $p = .944$, $\eta^2 < .01$; no significant interaction effect, $F(1, 35) = .30$, $p = .587$, $\eta^2 = .01$.

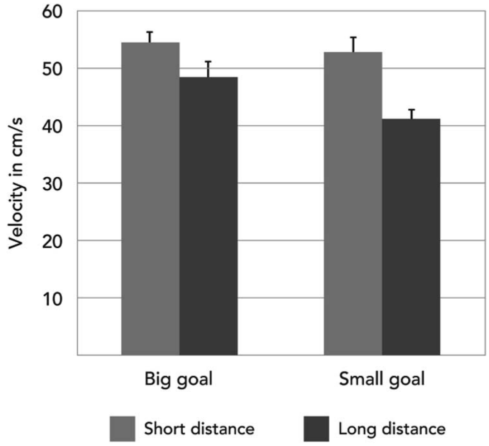

Figure 3. Peak velocity of the first movement unit in mm/s of the reach as a function of goal size (left cluster: big goal size; right cluster: small goal size) and goal distance (lighter gray bars: short distance; darker gray bars: long distance). There was a significant main effect of goal size ($p < .05$) and goal distance ($p < .01$). Error bars indicate the standard error of the mean ($n = 35$; $n_{...} = 19$, $n = 16$). Figure adapted from *Infants in Control: Prospective Motor Control and Executive Functions in Action Development* (p. 67), by Gottwald, 2016.

of their full reaching movements may be partly explained by the difficulty of the subsequent action. To our knowledge the current study is the first to investigate infants' prospective motor control in action sequences at the level of temporal precision related to the movement's inherent structure. It is also the first study investigating prospective motor control in action sequences in relation to Fitts' law. No prior study has attempted to directly model Fitts' law on multistep actions early in development. Additionally, the current study is the first that manipulated goal size *and* goal distance to directly model Fitts' law in infancy.

In line with our first two hypotheses, these findings indicate that peak velocity of the first movement unit of the reach was affected by the difficulty of the subsequent action. Infants appear to take action difficulty into account and plan their reaching action according to the difficulty of the future action. Their reaching was already faster at the beginning of their reaching movement, as indicated by a higher peak velocity of the first movement unit, when the subsequent action was easier to perform. It appears that infants prepare differently not only for different *action types* (as shown by Claxton et al., 2003, for 10-month-olds and Chen et al., 2010, for toddlers) but also for different degrees of *action difficulty* of the same action. Prior evidence has detailed this in 7-year-olds (Fabbri-Destro et al., 2009), but, to our knowledge, this is the first study indicating that the same is true for infants.

The second analysis of the study looked at whether infants would prospectively control their reaching movements according to Fitts' law (considering the difficulty of both goal distance *and* goal size) or by only difficulty aspect (goal size *or* goal distance). A version (Welford et al., 1969) of Fitts' law significantly explained 48% of the variance in movement duration for the placement action, where both difficulty parameters were directly manipulated. Both goal size and goal distance were significant predictors for movement time. This finding is consistent with our third hypothesis, that infants' actions are well described by Fitts' law and that, similar to the case for adults, their actions are influenced by both goal size and goal distance. With 45%, a similar high explanation of variance in movement times was found by Zaal and Thelen (2005) for 11-month-olds. Again, these authors

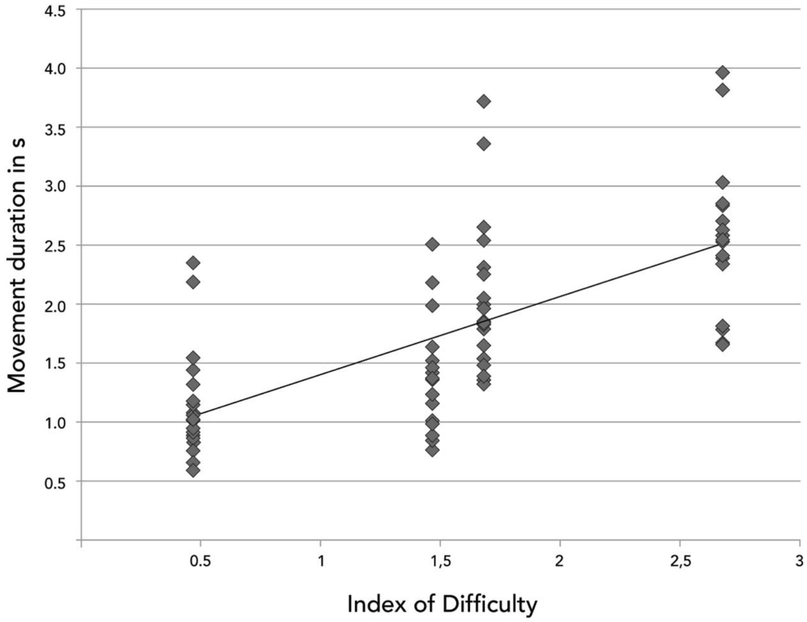

Figure 4. Placement movement duration as a function of the difficulty index, $\mathrm{ID} = \log_2(D) + \log_2(1/S)$. The line indicates the linear relation between ID and movement duration. Figure adapted from *Infants in Control: Prospective Motor Control and Executive Functions in Action Development* (p. 68), by Gottwald, 2016.

Table 1
Multiple Linear Regression Analyses Coefficients of the Placing and Reaching Durations with the Predictors Goal Size and Goal Distance

Action and predictor	*F*	R^2_{adj}	*b* (*SE*)	β
Placing	34.19***	.476		
Goal size			.654 (.08)	.654***
Goal distance			.393 (.13)	.250**
Reaching	3.15*	.056		
Goal size			.001 (.03)	.002
Goal distance			.111 (.04)	.286*

Note. Table adapted from *Infants in Control: Prospective Motor Control and Executive Functions in Action Development* (p. 69), by Gottwald, 2016.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

and Vishton et al. (2005) manipulated only goal size, not goal distance.

When action difficulty was held constant, however, as was the case in the reaching phase, the model significantly explained 6% of the variance in movement duration, albeit with only goal distance of the subsequent action as a significant predictor for movement duration of the current action. Given the general high variability in infant data and the fact that Fitts' law itself describes current actions, it is noteworthy that Fitts' law provides a significant contribution to explain the initial phase of a multistep action, where difficulty is not manipulated. However, 6% is a small amount, especially in comparison with an explained variance of 48% for the placement durations. Even though the difficulty parameters were held constant for the reaching action itself, the manipulated difficulty parameters of the subsequent placing action should have an impact, if Fitts' law has a large impact also in the beginning of the action sequence. Therefore, we expected Fitts' law to explain a larger amount of the variation in the reaching durations than the results demonstrate. This indicates that the movement duration of the pregrasping action is hardly influenced by the factors stipulated by Fitts' law. However, it might also be the case that our between-subjects design with two goal sizes and two goal distances failed to show existing Fitts' law effects.

Investigating movement durations, Claxton et al. (2003) did not find significant differences in infants' reaching based on the subsequent action. The results of the current study fit well with Claxton and colleagues' results, because we primarily found effects of the following action for movement velocity (as did Claxton et al., 2003) and fewer effects for movement duration (Claxton et al., 2003 found none). The measures of velocity and duration are obviously related, because the duration of a movement depends on, besides the involved distance, velocity. Should not both measures consequently give similar results? An important difference in the current study was that movement velocity was measured within the first part of movement—the first movement unit—and movement duration was measured for the full movement. This suggests that velocity of the first movement unit might be a more sensitive measure than is movement duration. We argue that this is especially the case because the first movement is thought to reflect prospective motor control, whereas the full movement additionally involves later occurring feedback processes.

Two caveats should be mentioned. First, in the context of the current study, action difficulty is defined on the parameters of goal size and goal distance, and the results should be interpreted with Fitts' law in mind. The current study shows the effects of the parametric differences of the subsequent placing part on the prior reaching part. Second, a number of infants (34%) had to be excluded from the analysis. Depending on the paradigm and the method utilized, relative high dropout rates of up to 50% are common in infancy research due to fussiness and habituation of the

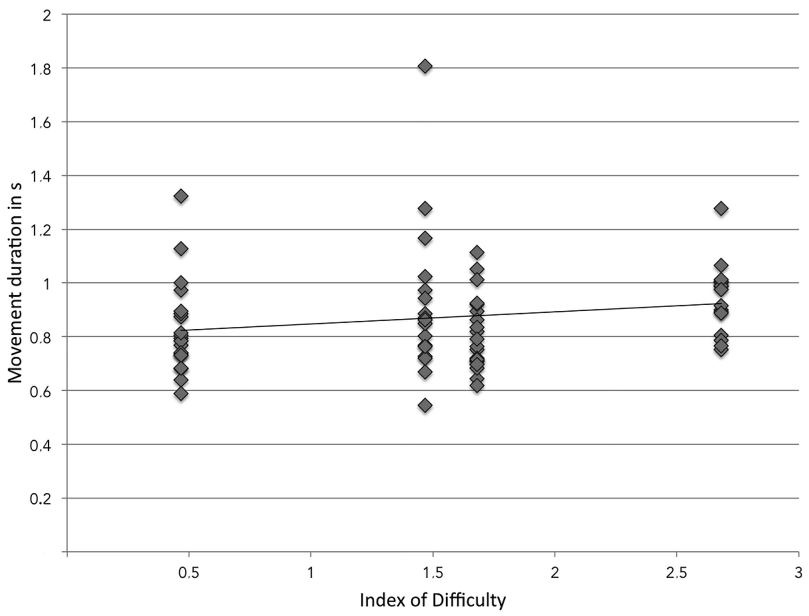

Figure 5. Reaching movement duration as a function of the difficulty index, ID = $\log_2(D) + \log_2(1/S)$. The line indicates the linear relation between ID and movement duration.

infants (cf. Claxton et al., 2003: 30%; Gottwald & Gredebäck, 2015: 39%; Zaal & Thelen, 2005: 23%). The amount 34% is within an acceptable range, especially given that the infants had to start their reaches from a defined area. In the studies just mentioned, infants could reach from wherever they liked to be included in the sample.

Additionally, in order to gain high-quality data we aimed for a high number of trials per participant and condition. The task itself was suited for infants at this age. Only five out of 56 participants did not want to perform it.

Future research in this area should investigate four important questions. First, it should select analysis variables that are not fixed (Claxton et al., 2003: 15 s; Johnson-Frey et al., 2004: 700 ms; Mash, 2007: 500 ms) but adjusted according to the infant's own actions. The peak velocity of the first movement unit (capturing approximately the first 200–600 ms of an action) is a promising measure that may be used to assess action planning across ages. By using the measure of peak velocity of the first movement unit, it is possible to study the movement characteristics themselves, rather than only the duration of movement. Second, future studies should also investigate whether infants younger than 14 months can prospectively control their subsequent actions based on difficulty of the same action type, ideally at the time when this ability exactly emerges in development. Another way to address the development of prospective motor control would be to study different age groups using the same tasks, as Wilmut et al. (2013b) did with older age groups. This might reveal, similar to in the latter-mentioned study, that infants of different ages use different strategies to prospectively control for different degrees of action difficulty. Third, it would be interesting for future research to investigate individual differences in prospective motor control. As Gottwald et al. (2016) and Chen et al. (2010) demonstrated, 18- to 21-month-olds differ in prospective motor control, and this might be the case for younger infants as well. It could also be that individuals use different strategies for planning their actions in multiple steps. Some might use goal distance, and others might use goal size as indicators of action difficulty in a Fitts' law paradigm. It is important that future studies investigate Fitts' law in action sequences in a within-subject design with more than two goal sizes and goal distances. Studies that include multilevel parameters might find more movement duration explained by the difficulty of the subsequent action. Finally, longitudinal work is needed to systematically address the development of Fitts' law in infancy. It is known that infants as young as 7–8 months (Vishton et al., 2005; Zaal & Thelen, 2005) perform their current actions according to Fitts' law but not whether actions of younger infants can be described by Fitts' law. It might well be that infants—when developing prospectively controlled reaching—around 5 months (von Hofsten & Rönnqvist, 1988) reach consistently with Fitts' law.

In conclusion, infants at the age of 14 months exhibit the ability to plan a sequence of actions and prospectively control the related movements. They not only prospectively control their current action (Gottwald & Gredebäck, 2015), but also consider their future actions. This requires taking the action context into account and preparing differently for different action types (Claxton et al., 2003), as well as making a sophisticated distinction between different degrees of action difficulty.

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