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Look before you reach: Fixation-reach latencies predict reaching kinematics in toddlers

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Abstract

Research on infant and toddler reaching has shown evidence for motor planning after the initiation of the reaching action. However, the reach action sequence does not begin after the initiation of a reach but rather includes the initial visual fixations onto the target object occurring before the reach. We developed a paradigm that synchronizes head-mounted eye-tracking and motion capture to determine whether the latency between the first visual fixation on a target object and the first reaching movement toward the object predicts subsequent reaching behavior in toddlers. In a corpus of over one hundred reach sequences produced by 17 toddlers, we found that longer fixation-reach latencies during the pre-reach phase predicted slower reaches. If the slowness of an executed reach indicates reach difficulty, then the duration of pre-reach planning would be correlated with reach difficulty. However, no relation was found with pre-reach planning duration when reach difficulty was measured by usual factors and independent of reach duration. The findings raise important questions about the measurement of reach difficulty, models of motor control, and possible developmental changes in the relations between pre-planning and continuously unfolding motor plans throughout an action sequence.

1 | INTRODUCTION

Infants learn about their world by acting in it. Reaching to and handling objects is thus a critical component of many developing abilities (e.g., Franchak et al., 2018; Iverson, 2021; Slone, Yu, & Smith, 2019; Sommerville et al., 2005; Yu & Smith, 2012). Reaching in everyday contexts recruits the whole body and requires efficient integration across perception and action. This integration by infants and children is a well-studied area of research (Boudreau & Bushnell, 2000; Claxton et al., 2003; Clifton et al., 1994; Corbetta et al., 2014; Jovanovic & Schwarzer, 2011; Keen et al., 2014; Robin et al., 1996; Soska, Rachwani, von Hofsten, & Adolph, 2019; Thibaut & Toussaint, 2010; von Hofsten, 1991; Weigelt & Schack, 2010). These studies show, for example, that *after a reach is initiated*, the grip shape and kinematics of the reach made by infants and toddlers are driven by both perceptual information about the object and goal-directed intentions about what to do with the object after the reach (Berthier & Carrico, 2010; Claxton et al., 2003; Fagard & Pezé, 1997; Gottwald et al., 2017; Lockman et al., 1984; von Hofsten & Rönnqvist, 1988). For most reaching actions, the eyes of the actor arrive at the target before the hand starts to move. This *pre-reach phase* is proposed to be when *initial visual information* that guides the reaching movement is gathered (Johansson et al., 2001). There have been few direct studies of the pre-reach phase and its role in motor planning and action execution in toddlers.

One recent study begins to shed light on the question of action planning, action execution, and visual information about a target object. Soska et al. (2019) tasked infants and adults to reach for objects while passively pivoting in a seated position—a task that requires fast planning and execution. Their study revealed that infants and adults both scaled reaches to the location of the target mid-turn and, critical to the purposes of the current study, reach planning depended on when the object was in the field of view. Open questions remain about the relationship between the *timing* of action planning during the pre-reach phase when infants presumably gather visual information for the subsequent actions and the resulting reach kinematics when the action is executed.

Here we employ a novel data collection methodology—integrating synchronized head-mounted eye-tracking and motion capture—to examine how the duration of the pre-reach phase relates to the kinematics of the reach. This fine-grained data allowed us to examine temporal dynamics of the perception–action loop to understand better real-time sensory-motor processes that support the development of reaching action. We chose to study toddlers in the second year of life, because this is a period of development that includes increasingly complex manual actions on objects (Borjon et al., 2018). Figure 1 illustrates the approach to linking action planning and action execution. First, the timing between the first visual fixation on the target object and the subsequent reaching movement toward the target object (the pre-reach phase) is considered the *movement-preparation* phase (Abrams et al., 1990)—the period in which visual information about the target is processed and used to construct initial motor plans. Within this temporal window, the *fixation-reach latency* (see Figure 1), provides a measure of the complexity or completeness of this planning. Next, we measured the reach kinematics and duration to index commonly-used properties of reach actions (Claxton et al., 2003; Thelen et al., 1996) and examined two possible relations between fixation-reach latency and the reach kinematics.

Our analyses were motivated by two possible relations between fixation-reach latency and the reach kinematics. The two opposing and untested hypotheses are motivated by the same conceptual framework: the forward model of action (Wolpert & Ghahramani, 2000) which suggests that the mature planning system predicts sensory consequences of an unfolding action by generating specific predictions or plans about the changing states of the sensorimotor system. Built upon this model, the main hypothesis predicts that longer reaches would be associated with longer planning

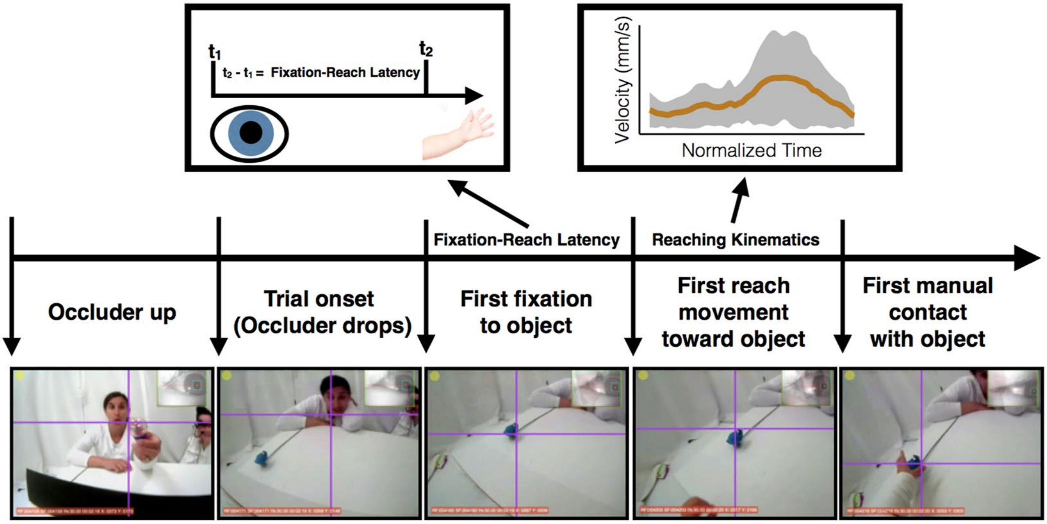


FIGURE 1 A schematic of one reaching trial. The trial begins with the occluder up. Trial onset begins when the occluder breaks a 90° plane. Fixation-Reach Latency is measured as the duration between the first fixation to the object and the first reach movement toward the object. Reach kinematics (velocity and duration) are computed between the first reach movement toward the object and the first manual contact with the object.

phases. This prediction derives from the idea that difficult reaches require more planning time and more time to execute. Difficulty can be viewed as an objective property of the reaching task or a psychological variable that varies across individuals so that the task factors that make a reach greater in difficulty for toddlers may be different from that in a mature system. Accordingly, we measured difficulty in two different ways: (1) our *performance* measure of a difficult reach was the duration of the executed reach, and (2) we also used *task* measures of reach difficulty including the distance of the reach target from the reaching hand. The second opposing hypothesis predicts that reaches shorter in executed duration are associated with longer pre-planning phases. This prediction derives from the idea that the rapid execution of a reach requires more planning time. Because the planning phase may involve simulating the reach afterward, longer planning would indicate more difficult reaches (by some measure of difficulty independent of reach duration) for the actor (Flanagan & Johansson, 2003; Stapel et al., 2015), it is also plausible that the duration of the planning phase could, in principle, be independent of duration of reach execution, our proposed performance measure of reach difficulty. The main goal of the present study is to determine these open relationships between the duration of the pre-planning phase, the duration of the reach execution, and other task-related measures potentially independent of the duration of the executed reach. This determination is a critical first step to the more systematic study of the pre-reach phase in infant goal-directed reaching.

To achieve this purpose, we chose a naturalistic reaching context in which toddlers were free to bend and reach with either hand while targets were presented in eight randomly-selected locations on a table. Because objects were presented at random spatial locations on a table, the toddlers, on every trial, had to first locate the target object visually and then—with reference to the current location of their hand and posture—plan the reach to the target. The children wore a head-mounted eye-tracker to measure object fixation and the kinematics of the reaches toward the objects were measured using a motion-tracking system. We report two sets of analyses, linking fixation-reach latency with measures of the kinematics of the reach and with assessments of non-kinematic task factors, respectively.

1.1 | Kinematic measures

In the first set of analyses, we focus on understanding the relation between fixation-reach latency and measures of the kinematics of the executed reach, all of which have been used as performance measures of reach difficulty (Corbetta et al., 2000; Thelen et al., 1993). We used common estimates of reaching kinematics—average velocity, maximum velocity, number of movement units, reaching straightness, and the duration of the reaching movement toward the object.

During execution, reaching velocity has been used to measure overall movement control and maximum velocity is generally considered to represent initial motor planning before movement feedback is integrated (Gottwald et al., 2017; Plamondon & Alimi, 1997; Von Hofsten, 1993). Number of movement units provides an index of hand-path smoothness and was estimated by an algorithm that identified local speed maxima in between two local speed minima, where the difference between the local maxima and both local minima exceeded 1 cm/s (cf. Thelen et al., 1996). Reaching straightness provides an index of how straight a reach was toward the target by estimating the ratio between the virtual path of a straight line from the initial location of reach onset and the target location and the actual path length. The initial ratio was standardized using the following Z-transform equation: $z(x) = 2\ln((1 + x)/(1 - x))$ (cf. Thelen et al., 1996) and increasing values indicate straighter paths. All of these factors, often correlated with duration of the executed reach have been used as measures of both reaching skill and reaching difficulty in measures of infant reaching performance. For example, the number of movement units indicates less skill and/or a harder reach. We report results from a number of independent statistical models with the main response variable being fixation-reach latency in the pre-planning phase. In this first set of analyses, then, the statistical models were constructed to test the relation between fixation-reach latency and measures of reaching execution.

One potential problem with using kinematic measures of the reach as the index of difficulty is that they are inherently time-dependent and also correlated to the duration of the executed reach. Thus, a correlation between the duration of the pre-planning phase and the duration of executed reach could be considered as showing a correlation between two non-independent factors: longer pre-planning predicts a longer time in reach execution.

1.2 | Non-kinematic measures

Accordingly, in the second set of analyses, we test for relations between fixation-reach latencies and measures of target difficulty that are (potentially) independent of the duration of reach execution. We use reach distance as our principal measure of task difficulty (Fitts, 1954). We used two separate measures of reach distance: target location (a factor variable) and the exact distance between the reaching hand at the onset of a reach and the target (a continuous variable). We also included reach type (contralateral/ipsilateral) in the statistical models to better understand how these results might be constrained by the lateralization of reaches. Contralateral reaches that cross the midline are often considered more difficult in the infant-toddler literature (Fagard et al., 2009) because young children tend to less frequently choose contralateral reaches.

2 | METHOD

2.1 | Participants

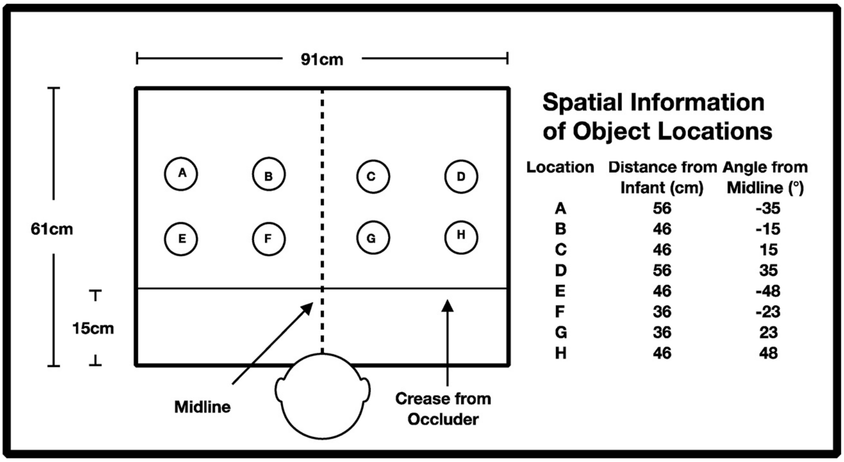
Seventeen toddlers participated (8 female and 9 male) in the study. The mean age of the sample was 22.28 months (*SD* = 1.89, Min = 18.20 months, Max = 24.90 months). The entire sample of toddlers was broadly representative of Monroe County, Indiana (84% European American, 5% African American, 5% Asian American, 2% Latino, 4% Other) consisting of predominantly working- and middle-class families. Toddlers were recruited through birth records and community organizations (e.g., museums, children's outreach events) that serve a diverse population. Ethical permission for the study was obtained from Indiana University's Ethics Review Committee.

2.2 | Apparatus

Participants were seated across from an experimenter at a table. The toddler sat in a custom high-chair and the experimenter sat on the floor. An occlusion board stood perpendicular to the table 15 cm from the edge of the table closest to the toddlers and when upright, occluded the entire surface of the table (91 cm × 61 cm) from the toddler. Eight predetermined spatial locations were used as shown in Figure 2 (four to the left of midline and four to the right of midline).

2.3 | Eye-tracking and motion capture

Children wore a head-mounted eye tracker (Positive Science, LLC). The head-mounted eye-tracking system included two cameras: (1) an infrared camera that is placed just below and is pointed to the right eye that records eye images, and (2) a scene camera that is placed low on the forehead and is pointed outwards captures the user's first-person view (90° visual field). The eye tracking system records egocentric-view video and gaze direction (x-, y-coordinates) in that view, sampled at 30 Hz. After the eye-tracker was securely affixed to the toddler, a calibration phase was completed. For calibration, an experimenter directed the toddler's attention toward a toy that was only used for calibration while another experimenter recorded when the toddler attended to the location of the toy. This procedure was repeated 15 times with the calibration toy placed in various locations on the tabletop. Another camera (30 Hz) was mounted above the table and provided a bird's eye view of the reaching trials. For capturing kinematic data from reaching, two sensors were sewn into wristbands and attached to the toddler's left and right wrist. The sensors were tracked by a motion tracking system (Polhemus,



Spatial Information of Object Locations

Location	Distance from Infant (cm)	Angle from Midline (°)
A	56	-35
B	46	-15
C	46	15
D	56	35
E	46	-48
F	36	-23
G	36	23
H	46	48

FIGURE 2 A bird's eye view perspective of the tabletop setup including spatial information about the object locations.

LLC) and generated x,y,z positional coordinates (120 Hz). One-dimensional velocity was calculated from the three-dimensional positional coordinates and the subsequent one-dimensional signal was smoothed with high-frequency components removed using a standard Kalman filter. The timestamps for the onset of data recording for the eye-tracking and motion capture systems were recorded and aligned in post-processing to ensure data streams were synchronized before proceeding with the data analysis protocol.

2.4 | Procedure

The reaching task consisted of the toddler reaching for attractive, graspable toys at eight spatial locations. Before each trial, the occlusion board was folded perpendicular and hid the locations for target placement from toddler view. The trial began with one experimenter moving a novel engaging toy (with blinking lights and sounds) laterally across the full horizontal length of the table while the toddler visually tracked it. When the toddler was fully engaged with the distractor and therefore not looking at the table surface, another experimenter randomly placed an object on one of the eight spatial locations behind the occluder and out of sight of the toddler. Once the object was placed, the first experimenter moved the distractor toy to the midline. Once the toddler's gaze was at midline and the toddler's hands were near the midline, the other experimenter unfolded the occlusion board, marking the onset of the reaching trial. At trial onset, the experimenter provided a verbal prompt encouraging the toddler to reach for the object. The reaching trial ended when the toddler reached and gained control of the object. The object appeared once on each of the eight spatial locations (see Figure 2). The high chair in which toddlers were seated allowed small trunk movements including leaning forward.

2.5 | Behavioral coding and analysis plan

On each trial, human coders identified the first visual fixation, that is, the first frame in which the fixation crosshair (see Figure 1) overlapped with the reaching target. The first fixation was used because toddlers rarely looked away from the object after the initial fixation. The onset of the first reaching movement was coded as the first frame when the toddler's hand started moving in the direction of the object, continuing past the plane of the occlusion board crease and ending with the toddler grabbing the target object. A second coder coded a randomly-selected 45% of trials and achieved high reliability, with onset agreement within 250 ms above 95% for first fixation (96%), reach onset (96%), and reach offset (100%). Ipsilateral reaches were coded when the reaching hand and the object were on the same side of the midline (see Figure 2), whereas, contralateral reaches were coded when the reaching hand and the object were on opposite sides of the midline. Reaching kinematics and reaching duration of the reaching hand were calculated from the onset of the trial to the offset of the trial which was determined as the first manual contact with the object.

Trials were excluded if there was an equipment malfunction (17 trials, 13%), if a toddler produced a ‘pre-reach’ that included a small movement toward the object followed by a recoiling of the hand back to the initial position (9 trials, 7%), or if the trial lasted longer than 15 s before a reach occurred or the fixation-reach latency was longer than 5 s (3 trials, 2%). Therefore, the final reaching corpus of reaches included 107 trials (out of 136 possible trials, 79%). Most trials (97% of the trials) were the first time to reach to a spatial location, so there was no motor memory involved. We analyzed the data at a corpus level of individual reaches while controlling for subject-level variability. With our final corpus, we conducted a power analysis using the SIMR R package (Green & MacLeod, 2016) that takes into account mixed effects models. We observed the power to detect an effect size of ~$\beta = .40$ was 1.0, 95% confidence intervals [96.38,100], which suggests high power to reject a null hypothesis of no trend among our fixed effects and dependent variable, given the properties of the final corpus. Average trial duration was 3412 ms ($SD = 1836$ ms). Twenty-nine trials (27.1%) were completed producing a contralateral reach and 78 trials (72.9%) were completed by producing an ipsilateral reach. Children were free to reach with either hand and contralateral and ipsilateral reaches were included in all analyses. Data and code are available on the Open Science Framework (https://osf.io/4fuhy/).

3 | RESULTS

3.1 | Analysis 1: Relations between fixation-reach latency and reach execution

To determine the relations between fixation-reach latency, reach kinematics, and reach duration, we used linear mixed effects (LME) models (Pinheiro, Bates, DebRoy, & Sarkar, 2007) with toddler ID as a random intercept. We also center-scaled our outcome and predictor variables so that the coefficients could be interpreted as standard deviations, that is, effect sizes (Keith, 2014). Toddler age (in days), trial order, reach type (ipsilateral/contralateral), and cumulative reaching distance were included as covariates. Note that cumulative reaching distance is a critical covariate because the kinematic variable controls for variability explained by the group-level variation in target location and also the small, but nevertheless important, individual-level variation of the start point of the hand at the onset of each reach. The utilization of LME models afforded the ability to test for *corpus-level* relationships between fixation-reach latency and reaching kinematics while controlling for variance attributed to by individual toddlers, trial order, and spatial location of object. Moreover, LME models are robust for datasets that exhibit between-subject variability in terms of the amount of trials that were completed and included in the final analysis for each subject. LME models allow researchers to include trial-level information instead of subject-level (averaged across multiple trials), which increases power and control over within-subject variance. In other words, LME models in the current paper assessed the relationship between fixation-reach latencies and reaching kinematics at a trial level.

3.1.1 | Results

Table 1 provides the summary statistics for fixation-reach latencies, reaching kinematics, and reaching duration. Table 2 provides summary statistics of the fixed effects from the mixed effects models, organized by the five dependent variables.

Longer fixation-reach latencies were associated with slower reaches when measured by average velocity, $\beta = -.36$, $p < .001$, maximum velocity $\beta = -.18$, $p = .025$, and reach duration, $\beta = .59$, $p < .001$. Longer fixation-reach latencies were not associated with number of movement units ($\beta = -.08$, $p = .332$) or straightness ratio, $\beta = .04$, $p = .693$. For all models, there were significant associations between the dependent variables and cumulative reaching distance: Slower reaching velocity and longer reaching durations were associated with more cumulative reaching distances; faster maximum reaching velocity was associated with more cumulative reaching distances; more movement units were associated with more cumulative reaching distances; lower straightness ratios

TABLE 1 Summary statistics of fixation-reach latencies and reaching kinematics.

Kinematics measure	All reaches	Ipsilateral (73% of reaches)	Contralateral (27% of reaches)
Average fixation-reach	787 ms (*SD* = 935)	838 ms (*SD* = 1012)	647 ms (*SD* = 680)
Average reaching velocity	200 mm/s (*SD* = 935)	185 mm/s (*SD* = 82)	241 mm/s (*SD* = 117)
Maximum reaching velocity	795 mm/s (*SD* = 323)	767 mm/s (*SD* = 321)	869 mm/s (*SD* = 320)
Reaching duration	2899 ms (*SD* = 1611)	2924 ms (*SD* = 1627)	2834 ms (*SD* = 1595)
Movement units	1.66 (*SD* = 0.94)	1.73 (*SD* = 1.06)	1.48 (*SD* = 0.69)
Straightness	1.45 (*SD* = 1.06)	1.32 (*SD* = 0.96)	1.79 (*SD* = 1.24)

Note: Standard deviations in parentheses.

(less straight reaches) were associated with more cumulative reaching distances. The overall pattern from the multiple measures in Table 2 supports the first hypothesis: longer planning durations were associated with differences in the execution of reaches in the direction of measures commonly associated with decreased reaching skill and/or reach difficulty. However, the number of movement units and the straightness ratio—two indices of reach quality or skill—were not associated with fixation-reach latencies. Observing that indices of reach speed (average velocity and maximum velocity) but not indices of reach quality (movement units and straightness ratio), suggests that perhaps there are components of reaching actions that are dissociated and distinct during the planning phase, at least for toddlers.

However, for many of the models, there were significant associations between dependent variables and reach type: Compared to contralateral reaches, ipsilateral reaches had slower average velocity, more movement units, and less straight reaches. Ipsilateral reaches which do not require the hand to cross midline are observed earlier in development than contralateral reaches and are often considered 'easier' (Fagard & Jacquet, 1996; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). To further test whether associations between dependent variables and fixation-reach latencies depended on reach type, we created a subset of models that limited reach trials to either ipsilateral or contralateral reaches. For both ipsilateral ($\beta = -.45$, $p < .001$) and contralateral ($\beta = -.53$, $p = .002$) reaches, there were significant associations between average velocity and fixation-reach latencies. For ipsilateral ($\beta = -.27$, $p = .006$) but not contralateral ($\beta = -.07$, $p = .664$) reaches, there were negative significant associations between maximum velocity and fixation-reach latencies: a finding that might be viewed as consistent with the aspects of the first hypothesis that differences in planning timing is associated with differences in reach execution. For both ipsilateral ($\beta = .68$, $p < .001$) and contralateral ($\beta = .39$, $p = .045$) reaches, there were significant positive associations between fixation-reach latencies and reach duration.

Finally, for many of the models, there were significant associations between several dependent variables and trial number: later trials were associated with slower average velocities, but faster maximum velocities, and less straight reaches. Overall, these results suggest that the period of time measured by fixation-reach latency is (1) associated with subsequent reaching kinematics and (2) specifically, that longer latencies are generally associated with slower subsequent reaches toward the target objects which could be an effect of competition between recently executed motor plans (Thelen et al., 2001). In aggregate, the results provide initial support for the hypothesis that the planning phase duration corresponds to the difficulty of the executed reach within the task context. Figure 3 shows the scatter plots for the five dependent variables on the y-axis and fixation-reach latencies on the x-axis. Note that many variables were plotted on LogLog axes as there was moderate positive skew. When positive skew was observed, results were replicated based on log-transformed variables in terms of alpha threshold ($p < .05$) and direction of the association.

TABLE 2 Summary of fixed effects model results from analysis 1.

Dependent variable	Effect	*B*	*t*	*SE*	*p*-value
Average reaching velocity	Intercept	−0.18	−0.80	0.22	.425
	Fixation-reach latencies	−0.36	−4.80	0.07	<.001
	Cumulative distance	0.26	3.34	0.08	.001
	Reach type	−0.34	−2.04	0.17	.044
	Trial	−0.10	3.12	0.03	.002
	Age in days	0.01	0.07	0.12	.947
Maximum reaching velocity	Intercept	−0.39	−1.71	0.22	.091
	Fixation-reach latencies	−0.18	−2.32	0.08	.025
	Cumulative distance	−0.45	5.58	0.08	<.001
	Reach type	0.01	0.04	0.17	.966
	Trial	0.09	2.77	0.03	.007
	Age in days	−0.05	−0.39	0.12	.702
Reaching duration	Intercept	0.16	0.82	0.19	.416
	Fixation-reach latencies	0.59	8.49	0.07	<.001
	Cumulative distance	0.48	6.89	0.07	<.001
	Reach type	0.09	0.58	0.16	.560
	Trial	−0.05	−1.72	0.03	.089
	Age in days	−0.01	−0.18	0.07	.863
Movement units	Intercept	−0.54	−2.23	0.24	.029
	Fixation-reach latencies	−0.08	−0.97	0.08	.332
	Cumulative distance	0.49	5.59	0.09	<.001
	Reach type	0.48	2.51	0.19	.014
	Trial	0.04	1.23	0.04	.221
	Age in days	−0.02	−0.17	0.11	.865
Straightness ratio	Intercept	0.80	3.02	0.26	.003
	Fixation-reach latencies	0.04	0.40	0.09	.693
	Cumulative distance	−0.44	−4.64	0.09	<.001
	Reach type	−0.60	−2.96	0.20	.004
	Trial	−0.09	−2.26	0.04	.027
	Age in days	0.04	0.32	0.13	.753

3.2 | Analysis 2: Relations between fixation-reach latency and target difficulty

To assess the relation between the fixation-reach latency and target difficulty, we used linear mixed effects (LME) models (Pinheiro, Bates, DebRoy, & Sarkar, 2007) with toddler ID as a random intercept. We also center-scaled our continuous outcome and predictor variables so that the coefficients could be interpreted as standard deviations, that is, effect sizes (Keith, 2014). Toddler age (in days), trial order, and reach type (ipsilateral/contralateral) were included as covariates.

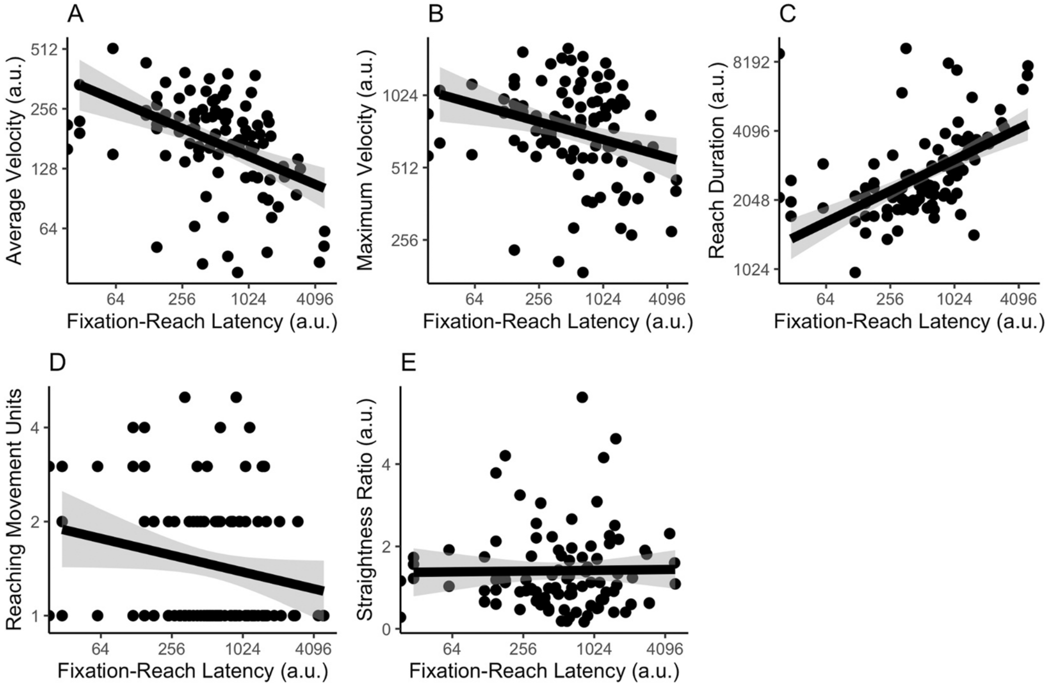


FIGURE 3 The relationship between fixation-reach latency and (a) average velocity, (b) maximum velocity, (c) reach duration, (d) movement units, and (e) straightness ratio in LogLog axes. Thick black line reflects group-level linear fit and translucent ribbon reflects ±95% CIs.

TABLE 3 Summary of fixed effects model results from analysis 2.

Dependent variable	Effect	*B*	*t*	*SE*	*p*-value
Fixation-reach latencies	Intercept	1.02	0.58	1.74	.562
	Target location (factor)	0.17	1.86	0.09	.066
	Reach type	1.14	2.10	0.54	.038
	Trial	0.02	0.46	0.04	.656
	Age in days	−0.003	−1.26	0.002	.228
	Reach type × target location (factor)	−0.17	−1.86	0.10	.065
Fixation-reach latencies	Intercept	1.82	1.10	1.65	.273
	Target distance (continuous)	0.02	0.15	0.15	.882
	Reach type	0.19	0.78	0.24	.438
	Trial	−0.002	−0.05	0.04	.958
	Age in days	−0.002	−1.21	0.002	.244
	Reach type × target distance (continuous)	−0.06	−0.28	0.21	.779

3.2.1 | Results

Table 3 provides summary statistics of the fixed effects from the mixed effects models, organized by the two separate independent variables, Target Location (on the table, factor) and Target Distance (from reaching hand, continuous). Fixation-reach latencies were not associated with different target

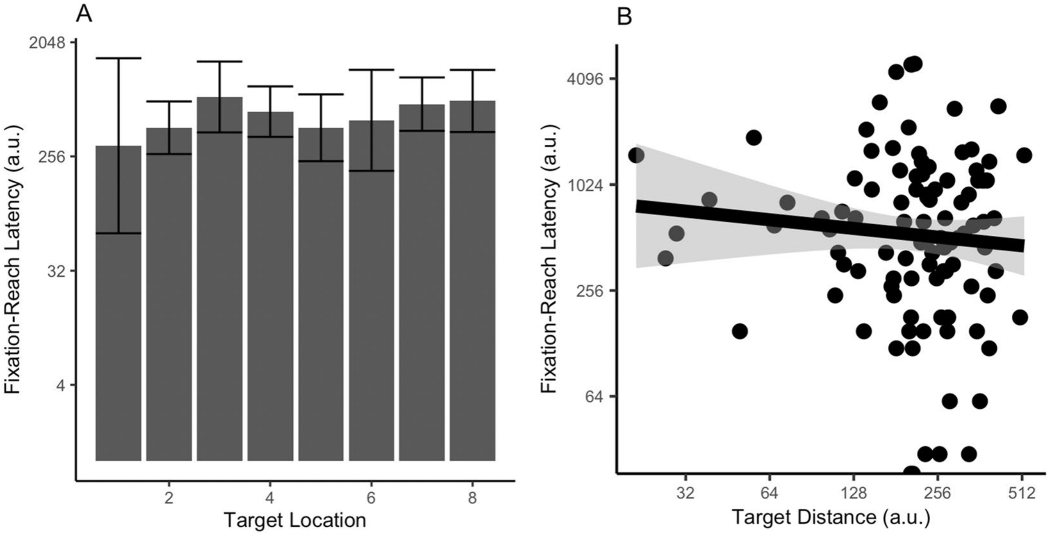


FIGURE 4 The relationship between fixation-reach latency and (a) target location and (b) target distance in LogLog axes. Thick black line reflects group-level linear fit and translucent ribbon reflects ±95% CIs.

locations (factor variable), $\beta = .17$, $p = .066$, nor with target distances (continuous variable), $\beta = .02$, $p = .882$. In brief, target difficulty, which we indexed with two measures of target distance, was not related to the duration of fixation-reach latencies (see Figure 4).

4 | DISCUSSION

When reaching for an object, the time between the visual fixation of the target object and the initiation of the reach is considered to be when visual processing of the object and the construction of initial motor plans occur (Abrams et al., 1990; Hayhoe et al., 2003). The present results show that, in toddlers, longer planning is generally related to slower reaches but not to measures of the quality of the reach or the difficulty of the reach defined in terms of location. More specifically, the duration of planning is related to the speed and timing of the executed reach: longer fixation-reach latencies in pre-reach predicted slower reaches and shorter fixation-reach latencies predicted faster reaches. This pattern implicates a common metric in planning a reach and in executing it. Although children at the age of those in this study have been reaching for many months, their reach kinematics, their ability to adjust reaches to specific conditions, and their ability to preadjust grasps to specific objects are not highly skilled, although developing rapidly (Jung et al., 2018). One implicated hypothesis that needs further empirical testing is this: Longer pre-reach phases are associated with longer reaches, because the planning phase simulates the reach itself. That is, the duration of the pre-reach phase is associated with the duration of motor execution but not with the quality of the reach as measured by movement units and straightness and not by the distance of the target.

These observations raise a number of open questions and opposing hypotheses about motor planning in toddlers, a period of marked increase in reaching and manual actions on objects but one that may also contain pockets of more and less skill. We offer two hypotheses about the findings and their implications for the development of pre-planning reaches to manipulated objects.

Hypothesis 1. Pre-planning followed by during-reach adjustments

Reaching to manipulate an object is, for toddlers, a mixture on pre-planning and on-line adjustments. The experiment used different spatial locations of objects so that the toddler could not predict the reach direction ahead of fixating on the object. The present findings suggest that important components of action planning occur before the initiation of an action, sufficiently so that there is a relation between planning duration and the execution of the reach. However, the present findings do not mean that the plan is fully completed prior to the initiation of the reach. Prior work shows the importance of during-reach adjustments for visually-guided prehension: a key role for the visual information during planning and executing actions (Claxton et al., 2003; Clifton et al., 1994; Soska et al., 2019). Many studies showing on-line adjustments post reach initiation have focused on object properties (handle type and location) and the intentions of the child (Claxton et al., 2003; von Hofsten & Rönnqvist, 1988). The present findings show the role of pre-planning on the temporal properties of the reach, but not hand adjustments. The observed lack of a relation between fixation-reach latency and reach quality and target distance in the present study is consistent with toddler reliance on both pre-planning and online adjustment after the initiation. This mixture of reach planning and hand adjustments to fit the grasp of the object may have different developmental trajectories in everyday reaches of toddlers in the real world as well in the present study. A key focus for future work is on the unfolding of motor plans for different reach properties and tasks over the course of the entire reaching sequence (Fleming et al., 2002).

Hypothesis 2. Reach difficulty as a complex and idiosyncratic property for toddlers, highly dependent on the individual's skills, reaching history, and motivations

The present findings indicate that the field needs a better understanding of the relationship between fixation-reach latencies, reaching kinematics as a function of the cascading effects of different motor abilities and other developments such as top-down versus bottom-up processes. For example, there are indicators that postural stability impacts the quality of sensorimotor integration (Bertenthal & Von Hofsten, 1998; Rachwani et al., 2013; Rachwani et al., 2015; Spencer et al., 2000). In another, more recent example, Gottwald et al. (2016) demonstrated that, for toddlers of similar ages as in the current study, reaching kinematics differed as a function of action difficulty in a Fitt's law paradigm. One might argue that a stronger test of the extent to which effective implementation of motor plans during the pre-reach phase occurs (or does not occur), could entail the utilization of a Fitt's law paradigm to parameterize action difficulty. If increasing task difficulty does not lead to changes in the relationship between fixation-reach latencies and reach kinematics, a more conclusive interpretation would be warranted in terms of the extent to which motor plans are being generated during the pre-reach phase. However, pre-reach planning in toddlers may be more complicated and less clean, including for example, a decision to reach with one hand or the other, interference from recently activated motor plans, and/or long-term history of reaching trajectories. Moreover, the role or arousal or the salience of the target may play a role in pre-planning or in rapid selection or inhibition of a motor plan (Clearfield et al., 2006; Thelen et al., 2001). There are clear experiments that could be done in these regards, manipulating toddlers' history with individual object targets, directions of reaches, and salience properties of targets and measuring how relations among the duration of the pre-reach planning phase, the kinematics of the reach, and subject-independent measures of target difficulty change.

4.1 | Limitations

There are a number of limitations of the present study. First, while it is difficult to measure overall motivational factors of toddlers, such efforts were not implemented. We did observe that average velocity of reaches was slower in later trials but this could be due to reduced motivation or interference of prior executed reaches (Clearfield et al., 2006). Second, despite a power analysis suggesting that we had sufficient power to observe the effect sizes, our results are based on a limited number of trials and toddlers. Despite these limitations, the findings contribute to current understanding by examining the relation between the period from first fixation to the initiation of the reach and by showing that the duration of the period is related to the duration of the reach itself.

4.2 | Conclusion

The present study was motivated by the forward model framework of action (Wolpert & Ghahramani, 2000), which states that a planning system predicts the consequences of an unfolding action by generating specific predictions about the changing states of the sensorimotor system. According to this theory, fixation-reach latencies are caused by generating specific predictions and plans about the kinematic properties of the subsequent reaching action. Although the present results do not unambiguously show this model to be wrong, and it may well be correct for mature and skilled behaviors, the results do suggest that the development of motor planning may be more complicated and thus not well served by the forward model framework. Some of our results—namely the relation between a planning phase and reaching speed– are in line with general predictions made by the forward model framework of action but others, including the lack of relation to reach quality and target difficulty are not.

In summary, as toddlers begin interacting in more complex ways with their environment, there is an increasing need to effectively integrate information across multiple modalities. We demonstrated associations between fixation-reach latency, reaching kinematics, and reaching duration during early toddlerhood and found evidence that the speed of generating motor plans and executing subsequent actions is diagnostic of the overall coordination of vision and reaching (Corbetta et al., 2000; Thelen et al., 1993; Thelen et al., 1987). Cascading actions embedded in carrying out complex goals and efficiently interacting with objects involves many steps which in turn require various levels of planning (Wagman & Miller, 2003). The current study provides a springboard for developing a comprehensive theory of the development of action planning across more complex and naturalistic tasks by highlighting the pre-reach phase of an action sequence as a critical period of action planning.

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