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Manual action, fitting, and spatial planning: Relating objects by young children

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Abstract

This study uses motion tracking technology to provide a new way of addressing the development of the ability to prospectively orient objects with respect to one another. A group of toddlers between 16-33 months of age (N=30) were studied in an object fitting task while they wore reflective markers on their hands to track spatial adjustments in three dimensions. Manual displacements of the handheld object were separated into translations and rotations. Results revealed that younger children largely used a two-step approach in which they initially translate an object to a target and subsequently attempt to rotate the object to match the target. In contrast, older children evidence more advanced spatial planning and integrate translational and rotational components throughout the entire period when they are transporting the object to the target. Additionally, at the oldest ages, children show even further improvements in coordinating translations and rotations by using relatively shorter translations (i.e., covering less distance) and by avoiding unnecessary rotations of the object. More broadly, the results offer insights into how manual problem solving becomes more efficient and planful during the toddler years.

Keywords

object manipulation; planning; spatial ability; motion analysis; mental rotation

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1. Introduction

Many problem solving and tool use tasks require individuals to relate the orientation of an object to that of another stimulus, such as an object or aperture. For example, placing a flat head screwdriver into a screw requires appropriate alignment of the tip of the screwdriver with the indentation of the head of the screw. Plugging in an electronic device requires proper orientation when fitting a plug into the holes of an electrical outlet. The ability to perform these kinds of manual tasks efficiently underlies many forms of adaptive behavior and requires anticipatory adjustments when relating objects to other stimuli.

In the present study, we investigate the development of object fitting and more generally, the problem of aligning objects in relation to one another. In this work, we advance a spatial analysis to understand the development of object fitting. Specifically, we consider the kinds of spatial displacements that must be combined when transporting and aligning an object with an aperture. We describe this process as entailing spatial displacements where translations and rotations of the object need to be coordinated. During translations, the object's center of mass moves from one location to another. In rotations, only the orientation of the object changes (Landau & Spelke, 1988). Adults integrate translations and rotations effortlessly when fitting objects into apertures, typically aligning the object with the aperture by the time the object first contacts the aperture. In contrast, coordinating translations and rotations of objects presents challenges for young children, who often fail to initially align a handheld object with an aperture when attempting fitting. Indeed, it is typically not until the end of the second year that young children orient a handheld object to match the orientation of an aperture prior to contacting the aperture (Meyer, 1940; Örnkloo & von Hofsten, 2007; Shutts, Örnkloo, von Hofsten, Keen, & Spelke, 2009; Street, James, Jones, & Smith, 2011)

1.1 Visuomotor Coordination in Reaching and Grasping Tasks

Well before young children preorient handheld objects in the context of fitting tasks, they gain experience with a formally similar, yet simpler manual task: grasping objects in different orientations. When grasping objects in different orientations, individuals must bring the hand to a target location (translation) and they must align the hand with the shape or orientation of the object (rotation). By the beginning of the second half year, infants show improvements in translational movements, bringing their hands smoothly and efficiently to the location of a target (Berthier & Keen, 2006; von Hofsten, 1991). Soon afterwards, they show improvements in rotational displacements that can be considered prospective: they align their hands with the longitudinal axis of a horizontally or vertically oriented object before they contact it (von Hofsten & Fazel-Zandy, 1984; Lockman, Ashmead, & Bushnell, 1984; McCarty, Clifton, Ashmead, Lee, & Goubet, 2001; Wentworth, Benson, & Haith, 2000; Witherington, 2005).

Around the same time, infants also display the ability to prospectively align their hands with the orientation of an aperture. By 10 months, infants take into account aperture orientation when reaching through an aperture (McKenzie, Slater, Tremellen, & McAlpin, 1993) and by 16-18 months, toddlers are clearly successful at aligning their hands with a horizontally or vertically oriented slot (Street et al., 2011). Taken together, these studies indicate that by the time infants bring the hand to an object or aperture, they behave prospectively: infants match the orientation of the hand to that of the target. In spatial terms, before the end of the first year, infants have successfully combined translational and rotational displacements within these reaching contexts.

1.2 Visuomotor Coordination in Fitting Tasks

Although infants under one year preorient their hands when reaching to an object or aperture, it is not until more than a year later that they preorient a handheld object when fitting it into an aperture (Meyer, 1940; Örnkloo & von Hofsten, 2007; Shutts et al., 2009; Street et al., 2011). The reason for this asynchrony is not well understood (Lockman & Ashmead, 1983; Street et al., 2011). Based on the foundational work of Perenin and Vighetto (1988) and Milner and Goodale (1995) on the separate roles of the dorsal and ventral visual streams, investigators have explained this dissociation in terms of developmental differences in the maturation of these two visual streams (e.g., see Street et al., 2011). These and other researchers (Johnson, Mareschal, & Csibra, 2001) have suggested that vision for object recognition (i.e., the ventral stream) is more developed in toddlers than vision for action (i.e., the dorsal stream), such that difficulties in fitting reflect relative immaturity of the dorsal stream.

Nevertheless, there are limitations in using the dorsal/ventral pathway distinction to account for the developmental dissociation between reaching for objects in different orientations and aligning objects with other stimuli. First, both reaching for objects in different orientations and aligning objects with apertures presumably involve dorsal function or vision for action. In fact, both kinds of abilities (aligning one's hand with an aperture and fitting an object into an aperture) are compromised due to dorsal streams deficits (Atkinson et al., 1997; Dilks, Hoffman, & Landau, 2008; Perenin & Vighetto, 1988). There is no reason why immaturity of the dorsal stream should be unique to situations in which infants hold objects in their hands. Further, it is not clear whether the inability to align an object with another stimulus would reflect immaturity of the dorsal pathway alone and/or a lack of functional integration between the two pathways.

1.3 The Current Study

We suggest that before ascribing the manual changes in prospective object alignment to underlying neural development, it is important to understand the behavioral changes that underlie developmental advances in fitting. In much of the prior developmental literature on object fitting, the focus has been on whether the object is aligned with the aperture when the object initially contacts it (Meyer, 1940; Örnkloo & von Hofsten, 2007; Street et al., 2011). This focus, however, neglects full consideration of the process by which an individual integrates rotations and translations during the transport phase of the task. In work with adults on the neural bases of object prehension, researchers have divided the action into two separate components: reaching and grasping (Jeannerod, 1984). Bringing the hand to a target object and appropriately preshaping the hand relative to that object are two neurally distinct processes (Grafton, 2010), which require integrated coordination and planning. In a similar vein, we suggest that object fitting tasks also involve a transport phase in which two separable components must be combined: bringing the handheld object to the aperture and aligning the handheld object with the aperture. By examining fitting tasks throughout the entire transport phase -- that is, from picking up an object to transporting it to the aperture -- we can gain insights into how children attempt to combine translational and rotational displacements and age related changes in this overall ability. Whereas researchers have analyzed the ontogeny of object search (Landau & Spelke, 1988) and object perception (Eizenman & Bertenthal, 1998) tasks in terms of their underlying translational and rotational components, this type of approach has not been used in work on development of object alignment.

To address how young children engage in visuomotor planning and coordinate rotations and displacements when fitting objects, we adapted motion capture technology so that we could continuously track the spatial adjustments that children made during the transport phase of the task. Motion tracking systems can be used to quantify precisely changes in location and orientation of the handheld object, the two parameters relevant for considering translation and rotation, respectively. In the present study, we examined how toddlers (ages 16-33 months) fit a rod into a horizontal or vertical slot located some distance away on a table surface so that toddlers were required to transport the rod to the slot. We chose this age range based on prior work suggesting that this is the developmental period when children begin to show anticipatory adjustment during object fitting (Meyer, 1940; Örnkloo & von Hofsten, 2007; Shutts et al., 2009; Street et al., 2011). Additionally, the rod was presented either parallel (match condition) or perpendicular (mismatch condition) to the slot. The match condition technically requires only translation, however, the mismatch condition requires both translation and rotation. By tracking movements continuously, we were able to examine at a behavioral level how young children integrate translational and rotational movements as they attempt to fit an object into an aperture. More broadly, by focusing on the process whereby children coordinate translations and rotations, we begin to specify the changes that underlie advances in visuomotor planning.

2. Method

2.1 Participants

The sample consisted of 30 children (15 males, 15 females) ranging from 16 to 33 months of age (M = 24.4, SD = 4.5; e.g., see Figure 4 for the age distribution of the sample). Participants were recruited from local preschools in the New Orleans area and from responses to online community advertisements. The families of the participants were primarily Caucasian and middle class (Caucasian = 25, African American = 3, Asian = 2). Children received a small toy for their participation. An additional nine participants were tested, but were excluded from the final sample because they did not complete all eight trials of the fitting task.

2.2 Apparatus & Design

Children were seated at a table (62 cm × 122 cm × 67 cm) and were asked to reach for a wooden rod (13.5 cm in length and 2 cm in diameter) lying flat (in either a horizontal or vertical orientation relative to the child) on the table (see Figure 1). The rod was initially located approximately 35 cm to the right or left of children's midline. Children were instructed to use only their right hand if the rod was initially placed on the right side, and to only use their left hand if the rod was on the left side. Once they reached for the rod, children were required to fit the rod into a vertically or horizontally oriented slot (14 cm × 2 cm) located in the middle of the table. The slot was 4 cm deep.

Each child was presented eight fitting trials in randomized order, based on all possible combinations of rod orientation (horizontal/vertical), slot orientation (horizontal/vertical) and the rod's initial location (left/right of the child's midline) (see Figure 2). The slot's initial orientation was counterbalanced such that half of the participants were first presented with the slot oriented vertically.

In order to track movements of the hand and rod relative to the slot, reflective markers were placed on children's hands, the rod, and the slot. To place markers on children's hands, the experimenter used double-sided tape and placed one marker on the knuckle of the child's middle finger (3rd metacarpal), and two markers on the child's wrist (radial styloid and ulnar styloid). In addition, two markers were glued on the ends of the rod and two markers were affixed to the ends of the slot (see Figure 1). Hand movements were filmed at 240Hz using a 3D optical motion capture system (Qualisys) involving eight infrared cameras (ProReflex MCU 240) positioned in a semicircle around the front of the table. An external trigger was used to start and stop recording between trials. Trials were filmed at 30Hz with a video camera (Hi8 SONY Handycam) to record children's behavior.

2.3 Procedure

A parent or guardian brought each child into the lab. The child sat in a chair or on a parent's lap at a table with slot in front of him. As noted, reflective markers were placed on the child's hands, but given the age range of our sample, placing all the markers on the child's hands sometimes took a fair amount of time. If the toddler was reluctant to wear the reflective markers, the experimenter familiarized the toddler with the markers by either asking the parent to wear the markers, placing stickers on the toddler's hands and/or gradually placing one marker at a time on the child's hand until the child gave permission for another marker to be added.

The rod was initially presented either on the left or right side of the child, approximately 35 cm away from the slot. Before the test trials began, the experimenter first demonstrated the fitting task with the rod mismatched relative to the orientation of the slot. Sitting on the opposite side of the table from the child, the experimenter picked up the rod and placed it in the slot using the most efficient strategy of keeping the length of the rod parallel to the table and aligned with the slot. After the demonstration, the test trials began. The child was asked, “Can you put the stick in the hole?” The child was also told, “When I say, ‘Go,’ put the stick into the hole.” Each trial started when the child reached for the rod. The trial ended when the rod was placed in the slot or when the child released the rod from his/her hand.

2.4 Dependent Measures

We divided the task into three phases: reaching, transporting, and fitting. The reaching phase was defined as the time period when the child started to move his/her hand to reach for the rod, ending when the child grasped the rod. The transport phase was defined as when the child started to move the rod until the rod first contacted the slot. Finally, the fitting phase started when the rod first touched the slot and ended when the rod was completely inserted into the slot. These phases were determined by examining videos linked to the motion tracking data. The inter-rater reliability for two independent observers who coded 20% of the entire sample for the beginning and ending frame number for each phase was .99 (Pearson's *r*). All markers were labeled with Qualisys software (QTM Track Manager) and then exported to MATLAB for additional processing.

2.4.1 Initial contact of rod with hand—In order to determine whether toddlers showed prospective adjustments when initially reaching for the rod, the alignment of the hand relative to the rod was examined. The angle at first contact with the rod was based on two vectors. One vector was determined by the markers attached to the rod (see V_R in Figure 3a). The second vector was determined by the marker on the middle knuckle projected to the midpoint of the markers on the wrist (see V_H in Figure 3a).

2.4.2 Transport phase: Translation (efficiency ratio)—As noted, the transport phase began when the child started to move the rod and ending when the rod first contacted the slot. To examine the translation component during this phase, we computed the efficiency ratio defined as the distance traveled by the center of the rod from the initial location of the rod to the slot divided by the shortest possible distance between these two points. Thus, a ratio of 1.0 would indicate that children transported the rod using the most direct path to the slot. In contrast, a ratio of 2.0 would indicate that children transported the rod using a path that is twice the shortest possible distance to the slot.

2.4.3 Transport phase: Rotation during translation—Angle measurements during the transport phase were described in three ways: 3-dimensional (3D) angle, vertical angle, horizontal angle. The 3D angle was defined as the angle between the rod and the slot in 3-dimensional space. This angle was based on the two vectors associated with the rod and slot (see Figure 3b). The markers attached to the rod composed one vector (see V_R in Figure 3b). Markers affixed to the slot determined the other vector (see V_S in Figure 3b). The vertical angle is defined as the angle between the rod and the horizontal plane (as defined by the flat surface of the table). This angle was based on the vector of the rod (see V_R in Figure 3c) and the vector of the projection of the rod onto the horizontal plane (see $V_{R'}$ in Figure 3c). Finally, the horizontal angle is defined as the angle based on the vector of the projection of the rod onto the horizontal plane (see $V_{R'}$ in Figure 3d) and the vector of the slot (see V_S in Figure 3d).

Each of these angles was measured continuously during the transport phase. To adjust for differences in distance traveled, the length of all trials were standardized in terms of distance. Angles were analyzed at five points during transport (100%, 75%, 50%, 25%, and 0%). For the trajectories as a function of distance, 100% refers to where the rod was furthest from the slot, and 0% is where the rod first contacted the slot. (We also defined trajectories similarly based on the temporal duration of the trajectory. For the results presented subsequently, only the analyses based on spatial trajectories are reported, as similar findings were obtained when trajectories were temporally defined.)

2.4.4. Visual attention—To examine whether the children were visually attending to the task, we coded where they were looking (i.e., slot, rod, or away) during the transport phase of the task. The inter-rater reliability for two independent observers who coded 20% of the entire sample was 1.0 (κ).

2.4.5 Fitting duration—Fitting duration was the temporal interval between when the rod first touched the slot and when the rod was first completely inserted in the slot, defined by when the markers on the rod were no longer registered by the motion analysis system.

3. Results

As noted, data were collected from 30 children with 8 trials each yielding a total of 240 trials. Out of 240 trials, 6 trials from 3 children occurred in which they did not successfully fit the rod into the slot.

Generalized Estimating Equations (GEE) analyses (see Hardin & Hilbe, 2012) were used to explore each predictor's (age, slot orientation, hand used, and either rod orientation or match/mismatch condition) contribution to the dependent variable of interest. GEE is an extension of generalized linear models, allowing for the analysis of non-normally distributed, correlated data. All GEEs in these analyses employed a gamma distribution with a logarithmic link function because error terms were not normally distributed and positively skewed. To account for the repeated measurement, we used an exchangeable-correlation error structure (which similarly to a repeated measures ANOVA, assumes an equal level of correlation between all trials from each child). GEE significance testing uses the Wald 2 statistic to evaluate the overall improvement in model fit associated with each parameter. When appropriate, we used backward elimination procedures to arrive at parsimonious models (see Agresti & Finlay, 2009). The full factorial model was initially run with all interactions. Least significant factors (*p*-value above .05) were then removed, and the new model was then analyzed. We thus employed an iterative procedure where models were tested until only significant factors and interactions remained.

3.1 Reaching

The reaching phase began when the child started to move his or her hand to reach for the rod, ending when the child grasped the rod. We examined the angle between the rod and the hand when the child first touched the rod. The purpose of this analysis was to see if children appropriately aligned their hands with the rod's orientation. In the initial analysis, the angle defined by the hand and rod was regressed onto age, rod orientation, slot orientation, and hand using GEE. As expected, no effects associated with age (Wald χ^2_1=.01, p=.94), hand used (Wald χ^2_1=.01, p=.93), or slot orientation (Wald χ^2_1=.01, p=.93) were found, but rod orientation was significant (Wald χ^2_1=221.98, p<.001). Regardless of age, children appropriately oriented their hands when reaching for the rod. When the rod was placed in a vertical orientation the estimated marginal mean angle was 38.69°. In contrast, when the rod was placed horizontally the estimated marginal mean angle was 69.72°. This finding is consistent with previous evidence that infants during the second half-year already align the orientation of the hand with that of an object while reaching (von Hofsten & Fazel-Zandy, 1984; Lockman et al., 1984; Witherington, 2005).

3.2 Transport phase: Translation - Efficiency Ratio

The transport phase began when the child started to move the rod and ended when the child initially touched the slot with the rod. As noted, the efficiency ratio was computed as the distance traveled by the center of the rod from the initial location of the rod to the slot divided by the shortest possible distance between these two points. We followed standard practice and removed outliers, defined as all trials where the efficiency ratio exceeded 1.5 times the interquartile range (the difference between the value at the third and first quartiles) from the third quartile (Moore & McCabe, 1999). This resulted in 21 trials from 11 children being excluded from this analysis. (Similar results were obtained when all trials were used.)

We regressed the efficiency ratio using GEE and followed the modeling procedure explained in Section 3. A significant main effect of age was obtained (Wald $\chi^2_1=22.02$, $p<.001$; see Figure 4). Older children transport the rod to the aperture using a shorter route than do younger children, indicating that with increasing age, toddlers' translational trajectories are becoming more efficient.

3.3 Transport Phase: Rotation

We next examined the angle between the rod and the slot throughout the transport phase to determine when and to what extent children prospectively aligned the rod with the slot. Motion analysis data (Qualisys) were used to determine the position of the rod in relation to the slot. Angles measured during the transport phase were described in three ways: 3-dimensional (3D) angle, vertical angle, and horizontal angle. As described previously, the transport phase analyses are based on standardized spatial trajectories (see Section 2.4.3). Since the initial angle of the rod relative to the slot differed in the match and mismatch conditions, match trials were analyzed separately from the mismatch trials.

3.3.1 Rotation: 3D angle—The alignment of the rod relative to the slot when the rod was transported to the slot was examined as a function of distance traveled during the transport phase. Age and distance (100%, 75%, 50%, 25%, and 0%) of the rod to the slot were used to predict the 3D angle between the rod and slot during transport, separately for the match and mismatch conditions. Both analyses revealed significant main effects of age (Wald $\chi^2_1=44.76$, $p<.001$; Wald $\chi^2_1=17.40$, $p<.001$, respectively) and distance (Wald $\chi^2_4=30.10$, $p<.001$; Wald $\chi^2_4=53.05$, $p<.001$, respectively), along with significant Age × Distance interactions (Wald $\chi^2_4=21.92$, $p<.001$; Wald $\chi^2_4=86.97$, $p<.001$, respectively). Following the procedures outlined by Aiken and West (1991), the interactions between age and distance were plotted using the low, middle, and high values for age. As can be seen in Figure 5, children are orienting the rod similarly early in the transport phase, but by the time the rod touches the slot, only the older children are closely matching the orientation of the rod to that of the slot. Moreover, the trajectories indicate that the older children begin to make anticipatory adjustments at the outset of the transport phase, suggesting that older children evidenced planning early in the trial.

3.3.2 Point of contact: 3D angle—We next looked more closely at the rod's orientation at the first point of contact with the slot, given the focus of most prior fitting studies on this time point (Meyer, 1940; Örnkloo & von Hofsten, 2007; Street et al., 2011). Age, slot orientation, and match/mismatch condition were used to predict the 3D angle between the rod and slot when the rod first contacted the slot. GEE analysis revealed only a significant age effect (Wald $\chi^2_1=59.57$, $p<.001$). When the rod initially contacted the slot, older children had more closely aligned the rod with the slot (see Figure 6). Importantly, the absence of any significant interactions (*p*s > .20) involving slot orientation and match/mismatch condition indicates that children performed similarly regardless of whether the slot orientation and match/mismatch condition were initially the same or different.

3.3.3 Rotation: Vertical angle—

Next, we broke down the 3D angle into its vertical and horizontal components to determine if similar results involving rotation were found for each of these components.

The vertical angle between the rod and the slot can be used as an index of the degree to which toddlers tilted the rod in relation to the slot (see Figure 3c). Age and distance (100%, 75%, 50%, 25%, and 0%) from the slot were used to predict the vertical angle between the rod and slot during transport of the rod to the slot. Consistent with the previous analyses, for both match and mismatch conditions, the GEE analyses revealed significant main effects of age (Wald $\chi^2_1=38.99$, $p<.001$; Wald $\chi^2_1=19.11$, $p<.001$, respectively) and distance (Wald $\chi^2_4=71.44$, $p<.001$; Wald $\chi^2_4=21.80$, $p<.001$, respectively), along with significant Age × Distance interactions (Wald $\chi^2_4=67.59$, $p<.001$; Wald $\chi^2_4=26.80$, $p<.001$, respectively). As can be seen in Figure 7, the trajectories indicate that younger children rotate -- that is, tilt the rod more than the other age groups. In contrast, children around 24 months of age show planning as evidenced by their slight tilt of the rod (about 15°) in relation to the slot. Finally, children near 30 months show the most effective planning with respect to the vertical angle by keeping the rod relatively flat, tilting it less than 15° on average in relation to the slot during the entire transport phase.

3.3.4 Rotation: Horizontal angle—

We next considered the orientation of the rod in the horizontal plane throughout the transport phase. As noted, the horizontal plane is defined as the tabletop surface where the slot is located (see Figure 3d). For these analyses, we removed trials where children initially attempted to vertically insert the rod into the slot (defined as the vertical angle of greater than 45° when the rod first contacted the slot). We adopted this conservative strategy where large mismatches were excluded because children may not have been trying to align the long axis of the rod with that of the slot on the table. For this reason, 30 trials from 14 children were omitted leaving a total of 210 trials (see Figure 8). (The same significant effects as described below were obtained when all trials were used.)

The horizontal angle between the rod and the slot during transport was examined as a function of distance to the slot. Age and distance (100%, 75%, 50%, 25%, and 0%) from the slot were used to predict this angle. For both match and mismatch conditions, the GEE analyses revealed significant main effects of age (Wald $\chi^2_1=27.95$, $p<.001$; Wald $\chi^2_1=16.43$, $p<.001$, respectively) and distance (Wald $\chi^2_4=15.92$, $p=.003$; Wald $\chi^2_4=28.99$, $p<.001$, respectively), along with significant Age × Distance interactions (Wald $\chi^2_4=10.32$, $p=.035$; Wald $\chi^2_4=102.31$, $p<.001$, respectively). As can be seen in the match condition (see Figure 9a), the younger children fail to maintain the initial alignment between the rod and slot during transport. In contrast, the older children engage in little rotation and maintain the initial match as they transport the rod to the slot. In the mismatch condition (see Figure 9b), the younger children show little adjustment after the first quarter of the transport phase. In contrast, the older children show adjustments throughout the transport phase, progressively orienting the rod so that it is in closer alignment with the slot.

3.4 Fitting Phase: Duration

Fitting duration was defined as the time between the initial contact of the rod with the slot and when the rod was first completely placed in the slot. Fitting duration was regressed onto age using GEE. Because children did not orient the rod similarly at the first point of contact with the slot, the angle of the rod at the end of the transport phase was entered into the model as a covariate. A main effect of age was obtained (Wald χ^2_1=5.21, *p*=.022; see Figure 10), indicating that older children are more efficient when fitting the rod into the slot even when the rod's orientation at its first point of contact with the slot is statistically controlled.

3.5 Visual Attention

To address a potential reason for younger children's difficulty in pre-orienting the object in relation to the slot, we examined where children were looking during the transport phase of the task (slot, rod, or away). The results revealed that children were looking at the slot during the transport phase on virtually all trials. Out of the 240 trials, there were only 4 trials during the transport phase in which children attended to the rod (2 trials) or looked away from the apparatus (2 trials). When these trials were eliminated from the preceding analyses, the results remained the same. The findings on looking indicate that even the young children were visually attending to the critical features of the task. Problems in visual attention thus do not account for young children's difficulty in prospectively aligning the object with the slot.

3.6 Grip

Children typically used the same grip throughout an entire trial and this grip fell into one of two categories: a power or precision grip. In the present study, the power grip refers to a hand posture in which the fingers are wrapped around the rod and the fingertips touch the palm whereas the precision grip refers to a hand posture in which the rod is held between the fingertips and the thumb (a grip typically exhibited by older children). Not surprisingly, older children were more likely to use a precision grip (r=.38, *p*<.001). When entered into the GEE models alongside age and match/mismatch condition, grip type was not found to be a significant predictor of rod alignment at the point of first contact with the slot (3D angle – Wald χ^2_1=.87, *p*=.35; vertical angle – Wald χ^2_1=.92, *p*=.34; horizontal angle – Wald χ^2_1=.25, *p*=.62). These results suggest that young children's difficulty in aligning the object with the slot does not stem from problems in fine motor control.

3.7 Learning Across Trials

We examined whether there was evidence of learning across the eight trials each child received. Age and trial number (1-8) were used to predict the 3D angle, vertical angle, and horizontal angle when the rod first contacted the slot. No effects involving trial number were obtained (3D angle – Wald χ^2_1=5.15, p=.64; vertical angle – Wald χ^2_1=8.49, p=.29; horizontal angle – Wald χ^2_1=10.38, p=.17). Children did not do better (or worse) at performing the task as they gained experience over the course of eight trials.

3.8 Individual Strategies

To address the consistency of children's transport strategies, we looked at how children oriented the rod during the transport phase for every trial. The main goal in these analyses was to investigate whether individual children used a consistent or a variable pattern of rotation across trials. To address this question, we plotted the 3D orientation of the rod throughout the transport phase on each trial in a polar coordinate system, which provides a birds-eye view of the rod's orientation across time (see Figure 11). The graph can be best understood as looking straight down onto a hemi-sphere which has the rod attached in the center. Each circle represents the exact orientation of the rod at a given frame (sampled at 240 Hz) during the transport phase. If a child used a consistent strategy in orienting the rod during the transport phase, the trajectories from the different trials should largely overlap one another. If a child did not use a consistent strategy, we would expect the trajectories from different trials not to overlap greatly but instead show distinct trajectories for each trial. To illustrate, all of the trials from an 18-month-old and a 25-month-old are shown in Figures 11a-d.

To quantify the extent to which children used a consistent strategy, we divided the polar coordinate plot of the rod's orientation during the transport phase into a 10 × 10 grid. In this plot, elevation of the rod could range from 0-90° and orientation of the rod with respect to the table surface could range from 0-360°. We then counted the number of bins (out of 100) which a child traversed during all four of their Match trials and all four of their Mismatch trials. Low scores would indicate that children employed similar orientations and rotations throughout all trials while high scores would indicate variable orientations. Using GEE, we regressed this score onto age and condition (match vs. mismatch). Results revealed only a significant effect of age (Wald χ^2_1= 19.82, p<.001). It can be seen in Figures 11e and 11f that the young children traversed many different orientations, while the older children did not. Notably, this was the case even when the rod and slot were initially aligned in the match condition.

In a follow-up analysis, we investigated whether the degree of consistency (number of bins) during transport predicted how closely children aligned the rod with the slot at the first point of contact. Since age predicts both consistency (see above) and the alignment at point of contact (see section 3.3.2) we controlled for age in the following analysis. We used GEE to regress the average amount of misalignment at the point of contact onto the degree of consistency (number of bins), while controlling for age and condition (match vs. mismatch). Results show that consistency during the transport phase is a highly significant predictor of alignment at the point of contact (Wald χ^2_1= 11.17, p=.001), even when controlling for the age of the child.

Taken together, these analyses reveal that with increasing age, children rotate the rod more consistently during the transport phase across trials. Furthermore, when controlling for age, those children who showed more consistency throughout the transport phase (including some of the younger children) also did a better job of aligning the rod with the slot at first contact. Children's inconsistency suggests a lack of planning, possibly caused by the demands of coordinating both rotations and translations simultaneously.

4. Discussion

In this study, we provide a new way of addressing developmental advances in the ability to prospectively orient objects with respect to one another. We analyze the problem of fitting by considering the types of spatial displacements (translations and rotations) that children need to coordinate as they bring an object into alignment with an aperture. To do so, we developed new methods using motion capture technology to illuminate the process of visuomotor planning. By using motion capture technology, we were able to track continuously the spatial adjustments that young children made as they transported a rod that was to be fit into a slot. This process-oriented approach coupled with our spatial analysis reveals new information about the development of visuomotor planning. Our major findings specify how the translational and rotational components involved in object alignment each change with age and become coordinated. This work thus advances prior work on the development of object fitting where the immediate focus has been more on outcome (i.e., whether children prospectively align an object with an aperture--see Meyer, 1940; Örnkloo & von Hofsten, 2007; Street et al., 2011) than the process by which alignment is achieved.

Although previous investigators have explained the development of object fitting with reference to the maturation of the dorsal pathway (Atkinson et al., 1997; Street et al., 2011), we suggest that it is important to understand first what changes occur at a behavioral level in terms of process as well as outcome. The present findings, while not challenging the importance of the dorsal/ventral pathway distinction, nevertheless, suggest that whatever neural descriptions are put forth, they should incorporate developmental achievements involving the planning and integration of translational and rotational displacements.

The results of our spatial analysis provide new information about the development of object fitting and suggest the following sequence involving advances in the planning of translations, rotations and their coordination. Initially, children under 20 months of age approach fitting in a two-step manner. They do not coordinate translational and rotational displacements. The younger children achieve translations successfully by bringing the object to the aperture, but even the translation component is relatively inefficient. Additionally, the rotation component causes difficulty. The younger children fail to rotate the object so that it is aligned with the slot by the time of first contact. As a consequence, although children under 20 months of age eventually succeed in fitting the rod into the aperture, they take on average about three times as long as the oldest children to do so.

Subsequently, between 20 and 24 months of age children begin to show greater evidence of planning. They begin to integrate rotational and translational displacements, while also becoming more efficient in performing each type of displacement. They prospectively align the rod with a slot, which is consistent with prior studies on fitting (Meyer, 1940; Örnkloo & von Hofsten, 2007; Shutts et al., 2009; Street et al., 2011). Just as important, our findings indicate that translations become better planned and more efficient: 20- to 24-month-old children follow a more direct path to the slot. Nevertheless, they still aligned the rod with the slot relatively late during the transport phase.

Finally, closer examination of the data reveals additional information about the development of visuomotor planning between 24-31 months: children near the upper end of this age range showed planning from the very beginning of the transport phase, regardless of whether the rod and slot orientations are initially matched. The analyses of both the efficiency ratio (i.e., distance traversed during transport divided by the straight line distance between the rod and slot) and the vertical angle indicate how planning is reflected in the older children's actions. Throughout the transport phase the oldest children did not elevate the rod very much and kept it parallel to the surface. Put another way, they simplify the problem by reducing the dimensionality or the degrees of freedom associated with the task. They made efficient low-to-the-surface translations, which essentially preclude unnecessary rotation that the youngest children evidence while lifting the rod higher off the table during the transport phase. In short, the results from our process-oriented approach suggest that advances in spatial planning involving the coordination of translations and rotations underlie subsequent developments in aligning objects with apertures in the third year.

The difficulties that the younger children experience in coordinating translations and rotations and their lack of planning are noteworthy when we consider the results in the match condition. Recall that in this condition the rod is already aligned with the aperture at the start of the trial and thus subsequent rotation--physical or mental--is not technically required to fit the rod into the slot. Nevertheless, the younger children in the match condition do not maintain the initial match, providing clear evidence that a lack of planning undermines their performance. Further, when we examined whether individual children at the younger age levels used a consistent rotational strategy during the transport phase, we found that most of the younger children were quite variable in how they rotated the rod from one trial to the next. Additionally, regardless of age, children who showed more consistent and efficient rotational strategies during the transport phase pre-aligned the rod with the slot more accurately.

Why do young children show difficulty in prospectively aligning an object in relation to an aperture? Pre-aligning an object in relation to a slot is a complex cognitive-motor problem that involves the integration of a variety of abilities including visual attention, motor skill, object perception, planning, and perhaps mental rotation (Shutts et al., 2009). One possible reason for younger children's difficulty is that while transporting the rod, they do not attend to critical features of the task, especially the slot. Yet across the entire sample and on virtually all trials, children attended to the slot as they transported the rod.

Another possible reason is that young children's difficulties are primarily motor, tied to physical limitations in the manual actions that they can perform. Our results, however, show that grip pattern (power or precision) did not predict whether children prospectively oriented the rod in relation to the slot. Further, children were eventually successful at fitting the rod into the slot on virtually all trials, suggesting that even the youngest children understood the goal of the task. Thus, children's difficulties in pre-orienting the rod in relation to the slot should not be attributed to problems in fine motor control or ignorance of the end-state requirements of this task.

Still another reason for children's difficulties is that planning and formulating an appropriate action plan for object fitting may require mental rotation abilities. Yet even infants under six months of age appear capable of engaging in mental rotation, especially if they are allowed some prior hands-on experience with the objects to be mentally rotated (Möhring & Frick, 2013). And in the present match condition where mental rotation is not technically required, young children still encountered difficulty in pre-aligning the rod with the slot. Therefore, younger children's failure to prospectively align an object with an aperture is not likely due to an inability to engage in mental rotation. Nevertheless, linking prospective mental rotation with an appropriate manual action plan likely poses additional processing requirements that children must meet.

Along these lines, we highlight another set of demands to help explain why prospectively aligning objects with apertures is so taxing for younger children and can lead to problems in planning. When asked to fit a rod into an aperture, young children are faced with multiple challenges. They must execute an action plan in which they perform translations and rotations and coordinate them simultaneously while they transport the object to the slot. In addition, with the object being held, not only does the object function as an extension of the hand, but the configuration of the hand changes as well. As a result, the potential outcomes of manual actions need to be considered with respect to the positioning and orientation of the object and not the hand alone. Collectively, these demands, in addition to those having to do with maintaining visual focus, perceiving the task-relevant object relations and keeping the goal in mind (see Shutts et al., 2009), may exceed young children's processing capacities. As noted and in support of this idea, the younger children adopt a simpler two-step approach in which they perform the translation first and the rotation component next.

4.1 Conclusions

In conclusion, the study provides new methods and a new way of thinking about the emergence of spatial planning during the early childhood years in object alignment and manipulations tasks, more generally. Our process-oriented approach and precise measurements with 3D motion capture data extend previous findings (Meyer, 1940; Örnkloo & von Hofsten, 2007; Shutts et al., 2009; Street et al., 2011) on object fitting and provide new information about the development of spatial planning. We suggest that the difficulty children encounter when fitting objects into apertures can be described as a problem of coordinating rotations and translations when the configuration of the hand is changed by virtue of holding an object. More broadly, the ability to plan and coordinate rotations and translations in object relational tasks will help children to solve problems and use tools effectively and efficiently in their everyday environments.

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Highlights

- We use motion capture technology to address the development of object fitting.
- Manual displacements of the object were separated into translations and rotations.
- Younger toddlers use a two-step approach when fitting to match the target.
- Older toddlers integrate rotations and translations at some point during transport.
- Oldest toddlers evidence planning from the onset of the transport phase.

Figure 1.

The experimental setup – depicted here is a horizontal rod and vertical slot presented on the left hand side. Markers were placed on the 3rd metacarpal (knuckle), ulnar styloid (wrist), radial styloid (wrist), ends of the rod, and ends of the slot.

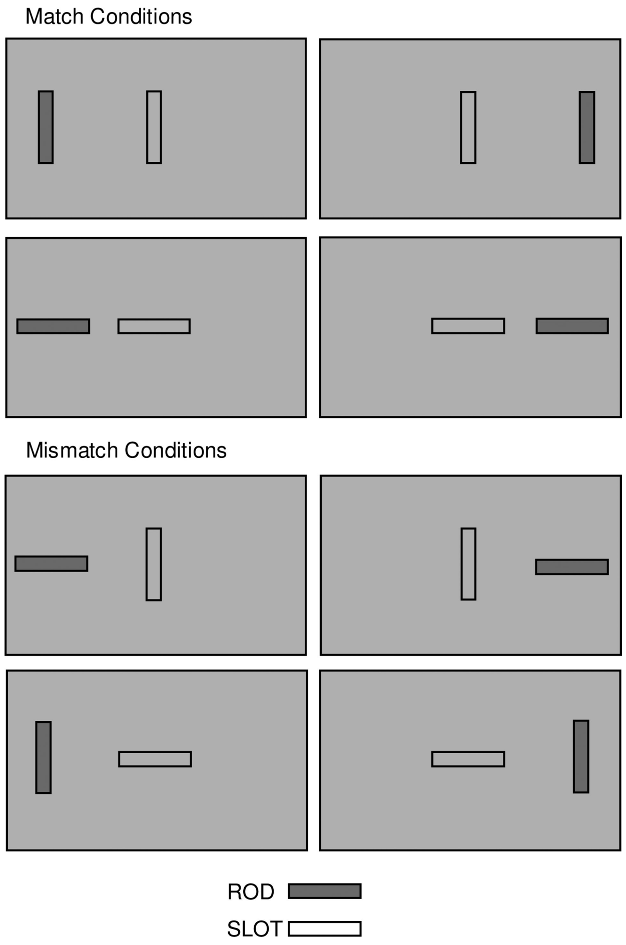

Figure 2.
The eight orientations of the rod and slot presented to the toddlers in the experiment.

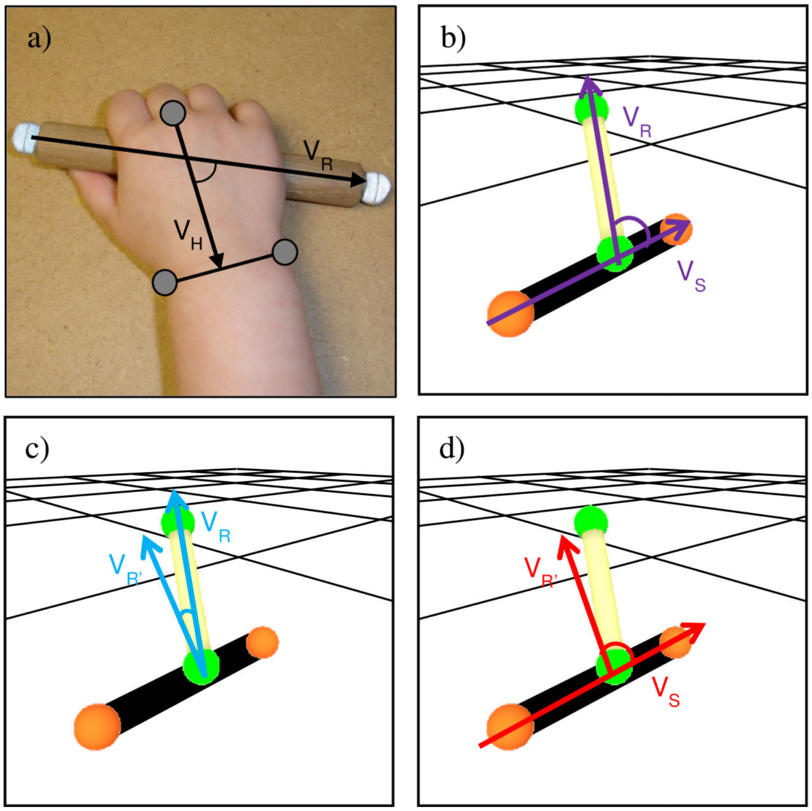

Figure 3.

V_H is the vector of the hand. V_S is the vector of the slot. V_R is the vector of the rod. $V_{R'}$ is the vector of the projection of the rod onto the horizontal plane. a) The angle of initial contact of rod with hand. b) The 3D angle between the rod and slot. c) The vertical angle between the rod and the horizontal plane. d) The horizontal

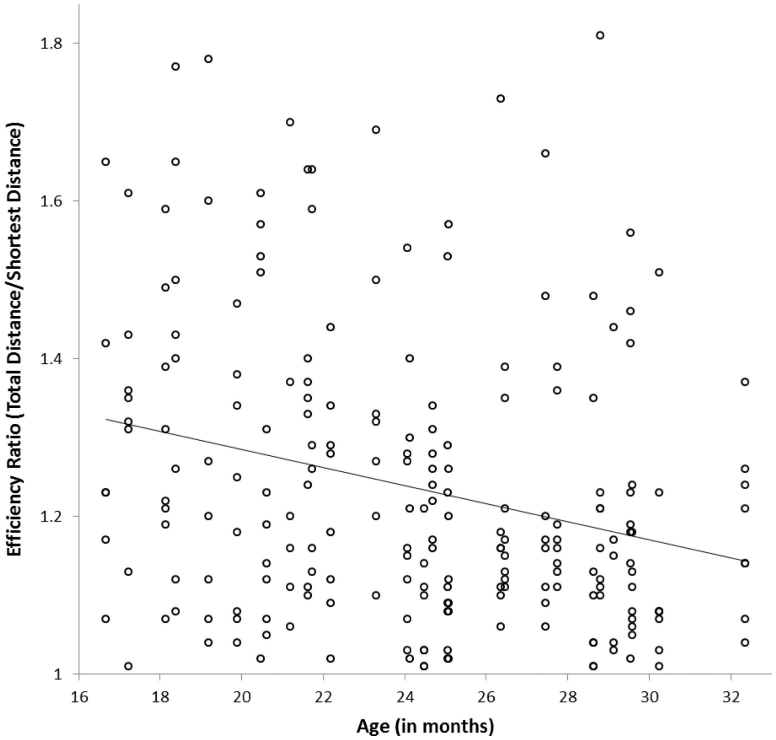

Figure 4.

Efficiency ratio for translations as a function of age. Each data point represents one trial. No two children were the exact same age, so the data at any given age come from a single child.

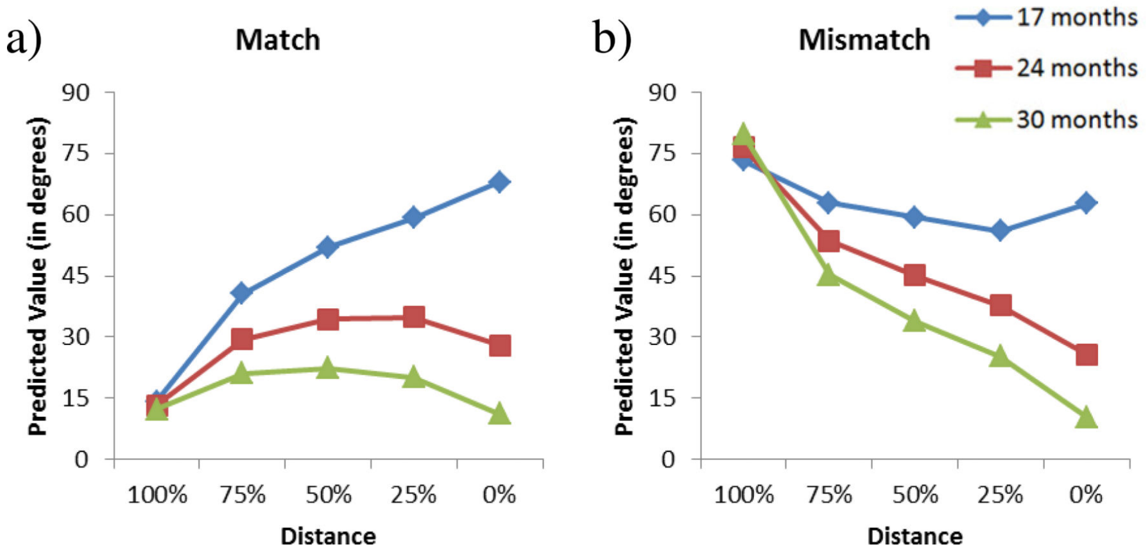

Figure 5.

Predicted values of 3D angles between the rod and slot of a) match and b) mismatch trials during the transport phase as function of distance. Fitting curves are representative of children in the lower (diamonds – 17 months), middle (squares – 24 months), and upper (triangles – 30 months) age ranges. Smaller predicted angles indicate closer alignment of the rod to the slot.

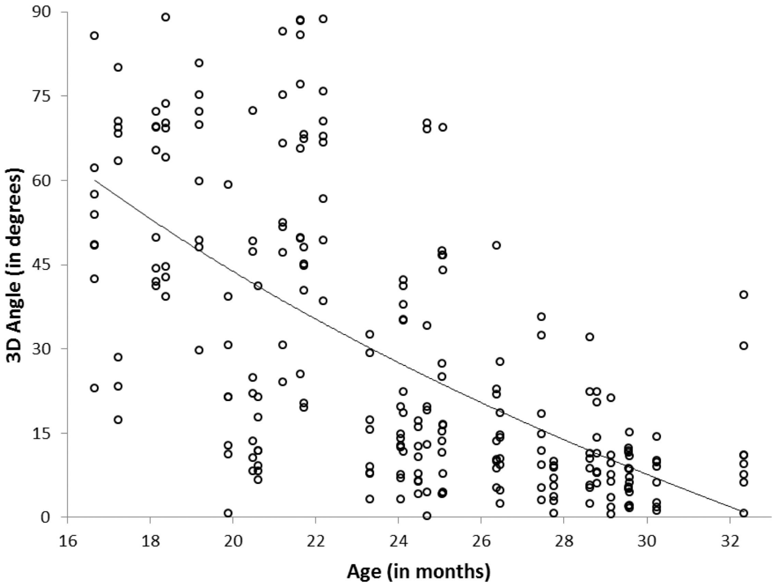

Figure 6.

The 3D angle when the rod first contacts the slot as a function of age. Each data point represents one trial.

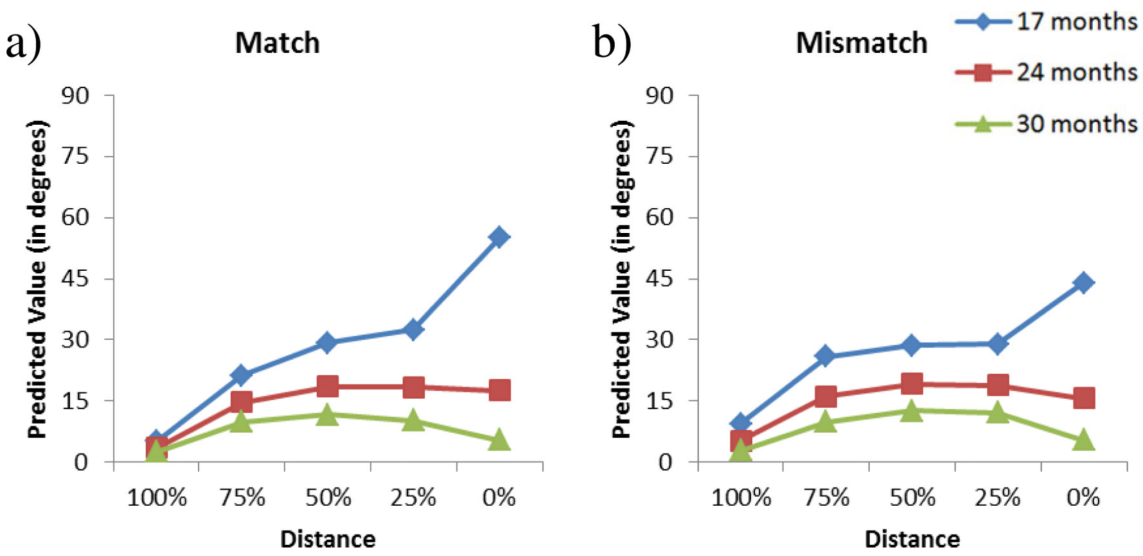

Figure 7.

Predicted values of vertical angles between the rod and slot of a) match and b) mismatch trials during the transport phase as function of distance.

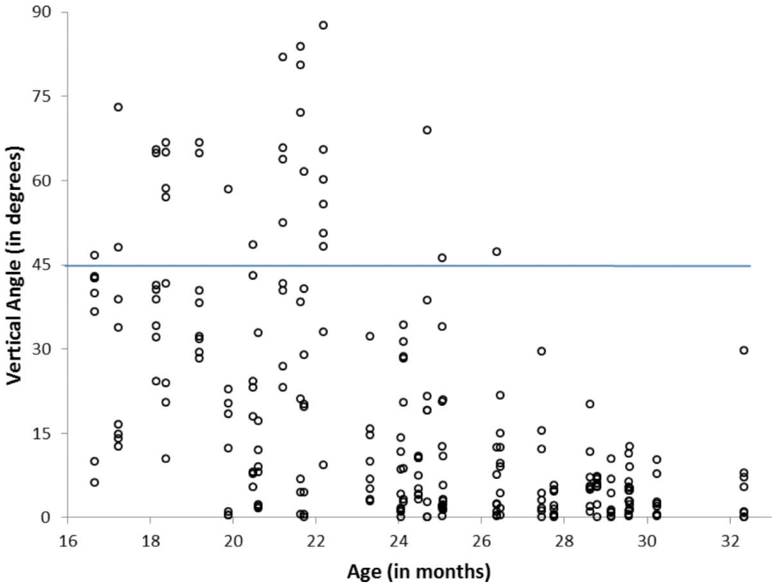

Figure 8.

The vertical angle when the rod first contacts the slot as a function of age. Each data point represents one trial. Trials above the 45° line were omitted from horizontal angle analyses, because children may not have been trying to align the long axis of the rod with that of the slot on the table.

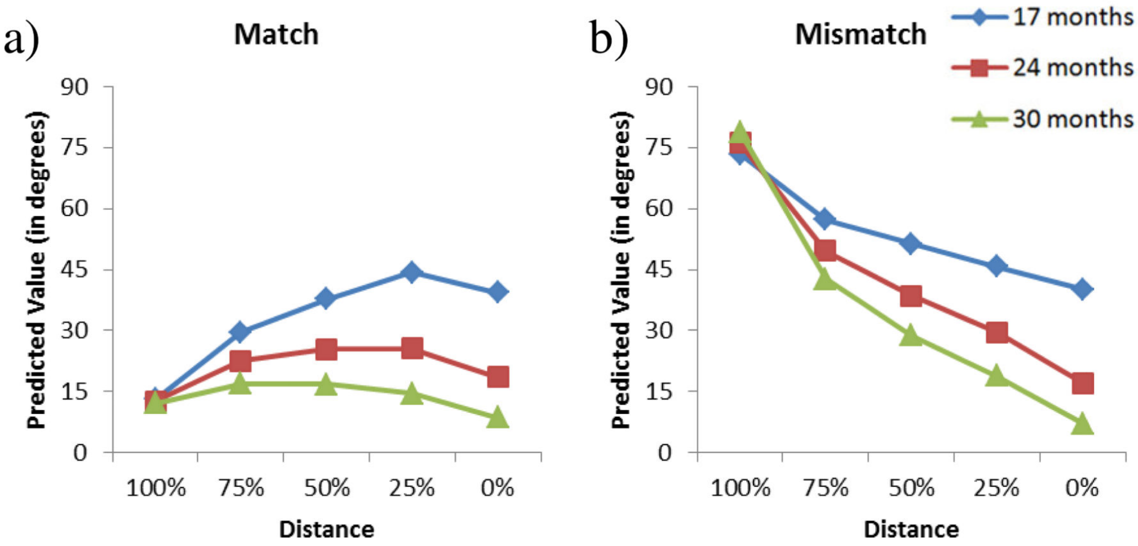

Figure 9.

Predicted values of horizontal angles between the rod and slot of a) match and b) mismatch trials during the transport phase as function of distance. Trials where the vertical angle at first angle of contact was greater than 45° were excluded from this analysis.

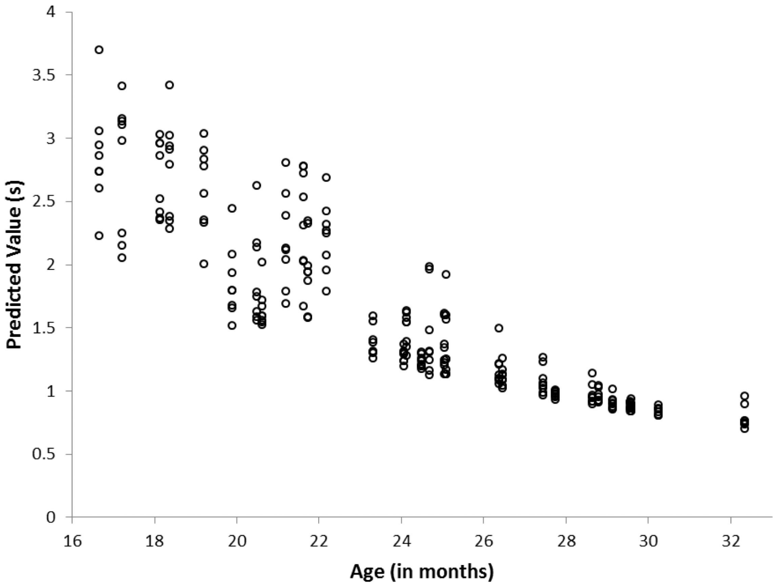

Figure 10.

Predicted value of fitting time as a function of age accounting for the degree of mismatch when the rod initially contacts the slot.

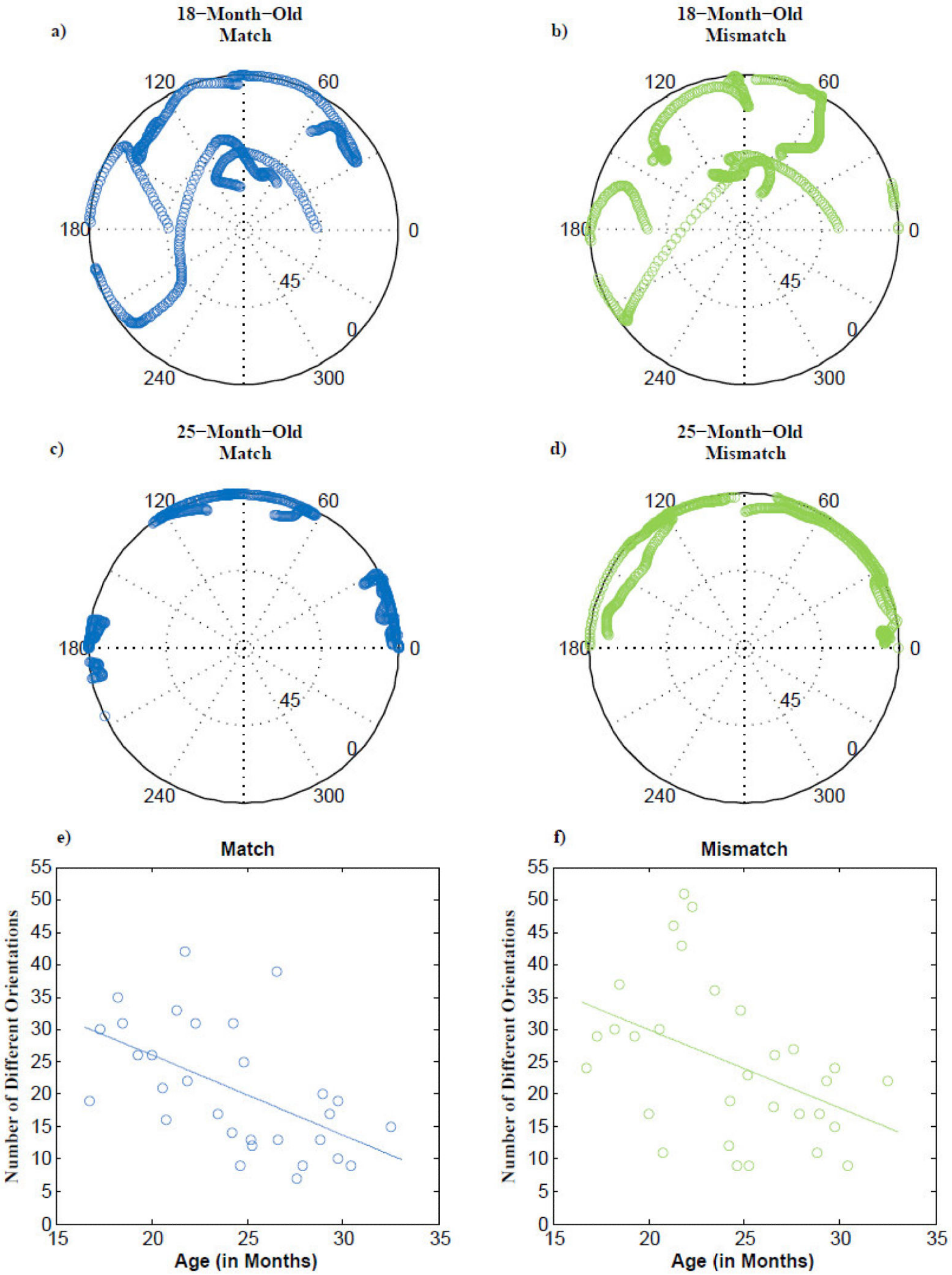

Figure 11.

The rotational trajectories of the rod during the transport phase for an 18-month-old in the a) match condition and b) mismatch condition and a 25-month-old in the c) match condition and d) mismatch condition. The number of different orientations which a child traversed during the transport phase in the e) match condition and f) mismatch condition.