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Means-End Problem Solving in Infancy: Development, Emergence of Intentionality, and Transfer of Knowledge

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Abstract

Behaviors and performance of 23 typically developing infants were assessed longitudinally at 6, 9, 12, 18, and 24 months in two means-end tasks: pulling a towel or rotating a turntable to obtain a supported object. With age, infants performed more goal-directed behaviors, leading to increased problem-solving success. Intentionality emerged earlier in the towel task than in the turntable task (6.9 vs. 10.8 months). Potential knowledge transfer between the tasks was first observed at 9 months. This study provides insight into the development of means-end learning, the emergence of intentionality, and potential transfer of knowledge in tasks involving a similar concept (support) but requiring different modes of action for success (pulling vs. rotating).

Keywords

means-end; problem solving; exploration; intentionality; transfer of knowledge

Means-end problem solving involves the intentional execution of a planned sequence of actions to achieve a goal (Brandone, 2015; Lobo & Galloway, 2013a; Piaget, 1953; Slater, 1995; Willatts, 1999). Examples of means-end tasks that infants learn to perform in the first years of life include removing a cover to retrieve a hidden object (Diamond, 1985; Piaget, 1953; Shinsky & Munakata, 2003), pulling a cloth to retrieve a distant object supported on the cloth (Munakata, McClelland, Johnson, & Siegler, 1997; Schlesinger & Langer, 1999; Uzgiris & Hunt, 1975; Willatts, 1984a, 1985, 1999), using the correct switch to activate a distant toy (Lobo & Galloway, 2008; Lobo & Galloway, 2013a), and pulling the correct string attached to a distant object to retrieve the object (Rat-Fischer, O'Regan, & Fagard, 2014; Richardson, 1932; Uzgiris & Hunt, 1975). In all of these means-end tasks, infants demonstrate an understanding that they can act upon one object to affect another object. Investigating these complex behaviors can provide insight into the mechanisms involved in early learning (Bonawitz et al., 2010; Brandone, 2015; Bremner, 2000; Csibra & Gergely,

2007; Gibson & Pick, 1988; Lobo & Galloway, 2008; Munakata et al., 1997; Willatts, 1999). Means-end tasks are considered important developmental tasks and are often incorporated in standardized developmental assessments (Bayley, 2006).

Requirements for Means-End Problem Solving

Means-end problem solving depends upon requisite motor skills like reaching and object manipulation, perceptual skills like visual attention to objects (Baillargeon, 1987; Gibson & Pick, 2000; Johnson, Slemmer, & Amso, 2004; Lobo & Galloway, 2008; von Helmholtz, 1962), and motor-perceptual coupling abilities (Case-Smith, Bigsby, & Clutter, 1998; Lobo & Galloway, 2008; Thelen, 1990). Means-end problem solving may also require cognitive abilities to distinguish between the means and end object, to understand the concepts of support and causal relations, to identify goals, to remember the consequences of previous behaviors on objects, and to select actions that will produce identified goals (Bremner, 2000; Piaget, 1953; Sommerville & Woodward, 2005a; Willatts, 1999).

Development of Means-End Problem Solving

Traditionally, successful means-end behaviors have been reported to emerge at about 5–6 months of age for less complex tasks, such as selecting the correct lever and visually attending to the resulting activation of a distant toy (Lobo & Galloway, 2008). By 7–8 months, infants begin solving means-end problems requiring one intermediate step, such as pulling a support to retrieve a distant toy (Clearfield, Stanger, & Jenne, 2015; Munakata et al., 1997; Willatts, 1984a, 1985, 1999). At 9 months, infants are capable of solving two-step problems, such as removing an obstructing barrier and then retrieving an object by pulling a support (Willatts, 1984a). At 10 months, infants can solve means-end problems requiring three intermediate steps, such as removing a barrier, pulling a cloth, and then pulling a string to bring a distant object within reach (Willatts, Forsyth, DiModugno, Varma, & Colvin, 1989).

While infants may spontaneously initiate and succeed in means-end problem-solving tasks in the first year of life (Bates, Carlson-Luden, & Bretherton, 1980; Diamond, 1985; Piaget, 1953; Uzgiris & Hunt, 1975; Willatts, 1990), means-end skills continue to develop and be refined throughout the second year of life (Brown, 1990; Casler & Keleman, 2005; Chen & Siegler, 2000; Nielsen, 2006; Rat-Fischer, O'Regan, & Fagard, 2012; Piaget, 1953).

Although there has been research interest in early means-end performance, previous research has typically been cross-sectional, has covered only short periods of developmental time, and has primarily focused on infants' trial outcome (successful/unsuccessful). Longitudinal research can uniquely serve to uncover developmental processes and underlying mechanisms of learning, while revealing rates and trajectories of change (Singer & Willett, 2003).

Emergence of Intentionality in Means-End Problem Solving

Intentionality is the deliberate or purposeful projection of awareness toward some object or outcome (Schlitz, 1996). Means-end problem-solving tasks can serve as effective tools for assessing intentionality in infants (Clearfield et al., 2015; Piaget, 1953; Schlesinger &

Langer, 1999; Uzgiris & Hunt, 1975; Willatts, 1984a, 1999). Piaget (1953, 1955) suggested that 4–8 month old infants lack the concept of causality, do not distinguish means from end, and may only accidentally solve a means-end task. Although infants might perform intentional goal-directed behaviors (e.g., pulling a support to retrieve a distant object) at 8–12 months, Piaget proposed that the true understanding of means-end relations (e.g., pulling the support only if the goal object rests on it) was achieved through active exploration (operationally defined as sensorimotor interaction with objects that provides the potential for information gathering) and experimentation only by 12–18 months. However, there is evidence that Piaget may have underestimated infants' understanding of support and means-end relations (e.g., Baillargeon, 1987; Goubet & Clifton, 1998; Hood & Willatts, 1986; Spelke, 1988; Willatts, 1999). For example, 7–8-month-olds have demonstrated an understanding of the concept of support and means-end relations (Willatts, 1999).

Intentionality in infants' means-end behaviors has traditionally been tested by including control trials without a toy (Munakata et al., 1997; Willatts, 1984a, 1999), using familiar vs. unfamiliar objects (Willatts, 1984a), or presenting “contact” vs. “noncontact” trials with the toy either placed on or near the support (Clearfield et al., 2015; Schlesinger & Langer, 1999; Uzgiris & Hunt, 1975). For example, in a task requiring cloth pulling to retrieve a distant, supported object, infants' behaviors have been considered intentional when they pulled the cloth more often during trials when a toy was supported on the cloth than during trials without a toy present (Willatts, 1984a, 1999). In this case, 7–8-month-old infants, but not 6-month-olds, have demonstrated intention in the means-end cloth-pulling task (Willatts, 1999).

The emergence of infants' intentionality in means-end problem solving may depend on the requirements of the task. It has been argued that intentionality appears earlier in means-end tasks involving supports, such as pulling a towel supporting an out-of-reach object, than in tasks involving surrounding means, such as using a hook to get an out-of-reach object (Bates et al., 1980; Schlesinger & Langer, 1999; Uzgiris & Hunt, 1975). This may be explained by the fact that general exploration of the means object in support tasks, but not in surround tasks, almost always results in translation of the end object, thus providing infants with information about the means-end relation. For example, infants have demonstrated intentionality by understanding the difference between “contact” and “noncontact” trials earlier (by the age of 8 months) in the cloth task than in the hook task (by 12 months; Bates et al., 1980; Schlesinger & Langer, 1999; Uzgiris & Hunt, 1975; Willatts, 1999). However, it is not clear whether two tasks with the same relational concept might differ in the timing of the emergence of intentionality if they require different manual behaviors for goal attainment. One might expect an earlier appearance of intentionality in a support task requiring pulling vs. rotation since the latter may be a more difficult concept to grasp during infancy (Bai & Bertenthal, 1992; Goldfield & Dickerson, 1981).

Transfer of Knowledge in Means-End Problem Solving

Transfer of knowledge is the dynamic application of cognitive and metacognitive strategies and general principles learned in one context (e.g., situation or task) to another context (Lauder, Reynolds, & Angus, 1999; Prawat, 1989; Renkl, Mandl, & Gruber, 1996). This

process often leads to the acquisition of new meaning and understanding, and is an important facilitator for learning and problem solving (Coleman, Brown, & Rivkin, 1997; Healy et al., 2002; Prawat, 1989; Price & Driscoll, 1997; Renkl et al., 1996; Singer, 1982).

Previous research has demonstrated a wide variety of transfer abilities in young children (e.g., Brown, 1990, Chen, Sanchez, & Campbell, 1997; Munakata et al., 1997; O'Connor & Russell, 2015). For example, Brown (1990) reported on the transfer of knowledge in problem solving by analogy in 2- and 3-year olds. The children were first trained to use a red-and-white hook to bring a distant toy within reach. Then they were presented with an analogous object retrieval task and given a choice of two tools: one similar in functional features (solid-colored hook), and the other similar in surface features (red-and-white stick). Three-year-olds, but not 2-year-olds, were able to choose the correct tool based on similarity of functional features. Chen et al. (1997) demonstrated the transfer of solution strategy in 13-month-olds, but not 10-month-olds, from modeled observation of a three-step means-end task involving a barrier, cloth, and string to a novel action task involving a similar structure but different objects.

In contrast to others who have documented transfer of knowledge between two tasks requiring the same motor actions on different objects, O'Connor and Russell (2015) documented transfer of knowledge between two tasks requiring not only different objects, but also different actions. They found that after being trained to bring a hidden toy into view by rotating a turntable, 7-month-olds were able to successfully solve the hiding-well search task. The authors suggested that infants' experience observing and comprehending the consequences of their actions, or 'insight into agency', in the first task facilitated the transfer of knowledge to the novel situation. This study, however, involved the provision of training or assistance to infants, and thus, does not provide insight into the spontaneous development of knowledge transfer.

Although previous studies have evaluated infants' performance in more than one means-end task (e.g., Clearfield et al., 2015; Schlesinger & Langer, 1999; Willatts, 1984a), none, to our knowledge, have comprehensively analyzed the data to assess for possible transfer of knowledge between different means-end tasks. This may be because most of the previous studies have been cross-sectional, while only a longitudinal design can help address this important developmental question.

Current Study

This study is innovative because it is the first to longitudinally and comprehensively assess behaviors performed by typically developing infants throughout the first two years of life in two means-end tasks that incorporate a similar concept (object support), yet require different manual actions (pulling versus rotating) to attain the task goal (grasping the end object).

The *first aim* of this study was to track behavioral performance and learning in two means-end tasks. We intended to enhance our knowledge about the behaviors infants engage in at different stages of means-end learning across age and to identify behaviors associated with successful means-end performance. Based on previous research, we hypothesized that

infants would display diverse exploratory behaviors toward the means and end objects and that these behaviors would become more goal-directed with age (Willatts, 1984a, 1984b, 1999). We expected greater performance of goal-directed behaviors to be associated with success in the tasks (Willatts, 1999).

The *second aim* of this study was to document the emergence of intentionality throughout the first two years of life in two means-end tasks involving the same relational concept (support) but requiring different manual behaviors (pulling versus rotating the support) to obtain the goal object. As in previous research, we measured intentionality as a shift towards more goal orientation in trials involving the end object relative to control trials without the end object present (Munakata et al., 1997; Willatts, 1984a, 1999). Intentionality was assigned when infants engaged in behaviors with the means object that could result in attainment of the end object more often in trials involving the end object than in trials without the end object. We hypothesized that the timing of the emergence of intentionality would differ across the two means-end tasks, emerging first in the towel task that required simple pulling and then in the turntable task that required rotation, a spatial translation more difficult to understand (Bai & Bertenthal, 1992; Bates et al., 1980; Goldfield & Dickerson, 1981; Schlesinger & Langer, 1999; Uzgiris & Hunt, 1975).

The *third aim* of this study was to determine whether infants were able to transfer their understanding of means-end relations across two tasks with a similar concept but different action requirements throughout the first two years of life. Based on previous research, we hypothesized that infants would demonstrate knowledge transfer between the two tasks within the first two years of life (Brown, 1990; Chen et al., 1997; O'Connor & Russell, 2015).

Methods

Participants

Power analysis was conducted in the validated program GLIMMPSE (<http://glimmpse.samplesizeshop.org/>) recommended for computing sample size calculations for longitudinal designs (Guo, Logan, Glueck, & Muller, 2013). At the target power 0.8 and Type I error rate .05, the estimated sample size ranged from 20 to 23 participants depending on proposed variance estimates, using both the Hotelling Lawley Trace and Wilks Likelihood Ratio statistical tests.

Parents of 23 full-term typically developing infants (13 males; Gestational age *Mean* = 39.4 weeks; *SD* = 1.1; 70.8% Caucasian, 20.9% African-American, 8.3% Asian; 4.2% with \$0–14,999 gross household income; 4.2% with \$25,000–34,999, 4.2% with \$35,000–44,999, 8.3% with \$45,000–59,999, 25.0% with \$60,000–79,999, 54.1% with greater than \$80,000) consented to participate in this study. There was no attrition of participants; 94% of visits and 93% of trials were completed across all participants. Recruitment from the local Delaware community was performed via word of mouth and mailed advertisements. Recruitment, informed consent, and data collection were completed in accordance with the regulations set by the University of Delaware's and Christiana Care Health System's Institutional Review Boards [The Relationship Between Early Brain Structure &

Development in Full-term & Pre-term Infants, University of Delaware IRB #128785–1, Christiana Care Health System IRB CCC# 27122, DDD# 504929]. Participants received monetary compensation for their participation in the study.

Procedure

Infants were assessed in their homes at 6, 9, 12, 18, and 24 months of age as they engaged in two means-end problem-solving tasks (Figure 1). Infants were in a positive or neutral behavioral state for all testing procedures to ensure the best performance. The towel task assessed their ability to retrieve a distant toy (end object) by pulling a towel (means object). Infants were seated in a high chair or on a parent's lap at a table. Testing included one No-Toy Trial with a 14" x 23" towel folded and placed on the table in front of the infant. Researchers attempted to attract infants' attention to the towel throughout the trial when infants were not visually attending to it for more than 5 seconds. The trial ended when 30-seconds elapsed (see Willatts, 1999): this time period was long enough to allow adequate exploration, and short enough to keep the infant engaged.

The No-Toy Trial was followed by 3 Toy Trials using the same towel presented as in the No-Toy Trial but now with a desirable toy placed out-of-reach on the far end of the towel (Figure 1A). The toy was selected from a small pool of salient similarly sized toys that were consistent across participants, and interesting across ages 6 to 24 months. Researchers attempted to attract infants' attention to the toy at the beginning and throughout trials when infants were not visually attending to it for more than 5 seconds by touching it and saying "Get the toy". Toy trials ended when an infant touched the toy, dropped the towel, or 30 seconds elapsed. The No-Toy trial was always presented before the Toy trials (similar to Willatts, 1984a, 1999) to capture behavior on the means object within sessions before infants experienced it as a potential tool to retrieve the distant end object.

The turntable task assessed infants' ability to retrieve a distant toy (end object) by spinning the turntable (means object). Testing procedures were the same as for the towel task, except a turntable was used instead of a towel (Figure 1B).

Assessments were video recorded using two camcorders for time-synched frontal and side views. Behaviors were coded using OpenSHAPA software. Across all the variables described below, intra-rater agreement was $95.7 \pm 1.5\%$ and inter-rater agreement with a primary coder was $90.3 \pm 5.2\%$ for 20% of the coded data; both based on the equation $[\text{Agreed} / (\text{Agreed} + \text{Disagreed})] * 100$.

Measures

All Toy Trials were classified as Successful or Unsuccessful. A Successful trial involved toy contact with prior visual attention to the toy in the 5 seconds before the contact (see Willatts, 1999); other trials were considered Unsuccessful.

Towel task.—The following behaviors were observed and coded: 1) *Touching the towel*—any part of the hand statically contacting the towel; 2) *Lifting the towel*—lifting at least half of the towel up from the surface without pulling it; 3) *Mouthing the towel*—towel in contact with the infant's mouth, tongue, or lips; 4) *Pulling the towel*—sliding the towel on the

surface; 5) *Reaching for the distant toy* – extending the arm(s) for the out-of-reach toy (Toy Trials only); 6) *Looking at the towel* – eyes directed at the towel; and 7) *Looking at the toy* – eyes directed at the toy (Toy Trials only). Each coded behavior was converted to percentage of trial time by dividing the cumulative duration of that behavior during a trial by the duration of the trial.

These behaviors were further categorized as *Goal-directed behaviors* or *Non-goal-directed behaviors*. We refer to the goal here as the means-end task goal of object attainment. Therefore, attention to the end object and behaviors that could potentially lead to the attainment of the end object were classified as goal-directed behaviors, while attention to the means object and behaviors that were unlikely to result in the attainment of the end object were classified as non-goal-directed. *Goal-directed behaviors* for the towel task included *Pulling the towel* and *Looking at the toy*. Note that although the performance of goal-directed behaviors increases the likelihood of success, it does not guarantee it per se: simply looking at the end object would not result in attainment of that object and pulling the towel could be too weak to move the end object within an infant's reach or too forceful, causing the end object to fall off the table and ending that trial. *Non-goal-directed behaviors* included *Touching*, *Lifting*, *Mouthing*, and *Looking at the towel*, as well as *Reaching for the distant, out-of-reach toy*. Reaching was included among non-goal-directed behaviors because, although brief instances of reaching preceded end object attainment in Successful Trials, reaching was more often observed for longer periods in instances where it was not a successful strategy (e.g., attempting unsuccessfully to reach for the distant toy). Note that for No-Toy Trials, *Goal-directed behaviors* did not include *Looking at the toy* or *Reaching for the toy* because a toy was not present. While No-Toy Trials did not allow for a specific means-end task goal, "*Goal-directed behaviors*" in this case served only as a control for comparison with the same behaviors during Toy Trials.

Turntable task.

The following behaviors were observed and coded: 1) *Touching the turntable* – any part of the hands statically contacting the turntable; 2) *Pulling the turntable* – attempting to slide the turntable on the surface; 3) *Banging the turntable* – hand(s) repeatedly hitting the turntable; 4) *Mouthing the turntable* – turntable in contact with the mouth, tongue, or lips; 5) *Alternate spinning of the turntable* – spinning the turntable cyclically in alternating directions through small or large ranges; 6) *Unidirectional spinning of the turntable* – spinning the turntable continuously in one direction; 7) *Reaching for the distant toy* – extending the arm(s) for the out-of-reach toy (Toy Trials only); 8) *Looking at the turntable* – eyes directed at the turntable; and 9) *Looking at the toy* – eyes directed at the toy (Toy Trials only). *Goal-directed behaviors* for the turntable task included *Alternate spinning of the turntable*, *Unidirectional spinning of the turntable*, and *Looking at the toy*. *Alternate spinning of the turntable* was included among goal-directed behaviors because it was often performed through a range large enough to result in end object attainment. *Non-goal-directed behaviors* included *Touching*, *Pulling*, *Banging*, *Mouthing*, and *Looking at the turntable*, as well as *Reaching for the distant toy*. For No-Toy Trials, *Goal-directed behaviors* did not include *Looking at the toy* or *Reaching for the toy*.

Statistical Analyses

Statistical analyses, unless otherwise specified, were conducted using Hierarchical Linear and Nonlinear Modeling Software (HLM; Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004), the most recommended tool for the analysis of longitudinal data, accounting for non-independence of multiple observations of the same participants. Linear and quadratic trends of change with age (variables *Age* and *Age*²) were tested; statistically non-significant trends of change were dropped from the final models. To ensure that the observed effects in the current study are not only statistically significant, but also meaningful, Cohen's *d* measures of effect size were reported: 0.2 small, 0.5 medium, 0.8 large, and 1.2 very large effects (Cohen, 1988; Sawilowsky, 2009).

Development of Means-End Problem Solving.—To describe developmental trends of behaviors performed by infants across age in each task, data for the three Toy Trials were averaged within each visit for each infant. Preliminary analyses determined there were no significant differences in infants' performance among the three toy trials. No-Toy Trial data were not included in these analyses. The trajectories of change in each behavior (including aggregated *Goal-directed* and *Non-goal-directed behaviors*) across age were evaluated using HLM, while including in the multilevel model each behavior as a dependent variable, and *Age* and *Age*² as independent variables.

Change in trial success rate with age was analyzed by examining the raw data plots presenting the percent of successful trials out of the total number of trials performed at each age for each means-end task. In addition, binomial logistic regression was performed to determine the effect of age on the likelihood of a successful trial outcome, while entering into the logistic regression model a binomial variable *Outcome* specifying the trial outcome (0 = unsuccessful trial; 1 = successful trial) as a dependent variable and *Age* as an independent variable.

Differences in behaviors performed during “Successful” vs. “Unsuccessful” trials were analyzed next. Each Toy Trial served as a separate entry. Each behavior (including aggregated *Goal-directed* and *Non-goal-directed behaviors*) was entered into HLM as a dependent variable, and *Outcome*, *Age*, and *Age*² as independent variables.

Emergence of Intentionality in Means-End Problem Solving.—To establish the timeline of the emergence of intentionality, we calculated a new variable (*Intentionality*) as a difference between the percent of *Goal-directed* and *Non-goal-directed behaviors* at each data point for each infant. The trajectory of change was then determined for *Intentionality* using HLM, which allowed us to find the estimated age when infants would be expected to shift from performing predominantly non-goal-directed behaviors towards more goal orientation (*Intentionality* = 0), thus suggesting the emergence of intentionality in each means-end task.

To further assess whether the observed behavioral shifts truly represented intentionality, we compared infants' behaviors between Toy Trials and control No-Toy Trials. Each behavior (including aggregated *Goal-directed* and *Non-goal-directed behaviors*) was entered in HLM

as a dependent variable, while a binary variable *Goal* specifying the type of the trial (0 = No-Toy Trials; 1 = Toy Trials), *Age*, and *Age*² were entered as independent variables.

Transfer of Knowledge in Means-End Problem Solving.—Only data for Toy Trials, averaged across the three trials, were included in these analyses. To determine whether the towel and turntable tasks differed in difficulty, infants' success rates were compared between the two tasks using binomial logistic regression, while entering into the regression model *Outcome* as a dependent variable and a binary variable *Task* (0 = towel task; 1 = turntable task) and *Age* as independent variables.

We assessed whether the prevalence of goal-directedness would always be demonstrated first in the towel task and then in the turntable task, rather than the other way around. Next, we determined the age when the majority of infants showed understanding of the task requirements for both means-end tasks, or, in other words, were able to transfer their means-end knowledge between the two tasks. Among the infants with more than 50% of their behaviors being goal-directed during the towel task, we estimated the percent with more than 50% of their behaviors also being goal-directed in the turntable task. Transfer of knowledge was considered to take place at the first point when the majority of infants (>50%) who showed goal orientation in the towel task also demonstrated it in the turntable task.

Results

Development of Means-End Problem Solving.

There was very minimal trial attrition: infants completed 98.8% of the trials in the towel task and 98.5% of the trials in the turntable task. Several variables produced a large frequency of zero values (95%; *Lifting the towel*, *Mouthing the towel*, *Mouthing the turntable*) and were excluded from the analyses of individual behaviors, but not from the analyses of aggregated behaviors. No statistically significant differences were found in infants' performance of the coded behaviors between the three Toy Trials within each visit (e.g., infants did not improve their performance from one trial to another), which justified the averaging of the data across the three Toy Trials.

Detailed information on statistical parameters of the following analyses is provided in online supplementary materials Table S1. As infants got older, they significantly changed their performance of all coded behaviors. In the towel task, infants spent less time statically touching the towel ($t(88) = 5.08$, $p < .001$, $d = 1.08$), and more time pulling the towel ($t(111) = 6.92$, $p < .001$, $d = 1.31$) and reaching for the toy ($t(111) = 2.63$, $p = .010$, $d = 0.50$) (Figure 2A illustrates the behaviors representing about 95% of infants' manual repertoire).

In the turntable task, with age infants decreased static touching ($t(108) = 5.07$, $p < .001$, $d = 0.98$) and banging ($t(108) = 2.44$, $p = .016$, $d = 0.47$) of the turntable, increased unidirectional spinning of the turntable ($t(86) = 2.19$, $p = .031$, $d = 0.47$) and reaching for the toy ($t(108) = 3.00$, $p = .003$, $d = 0.58$), and showed consistently low levels of pulling the turntable ($t(86) = 2.80$, $p = .006$, $d = 0.60$), whereas alternate spinning increased until 12

months and decreased thereafter ($t(108) = 2.46, p = .016, d = 0.47$) (Figure 2B illustrates behaviors representing about 80% of infants' manual repertoire).

Infants increased looking at the end object (Towel task: $t(88) = 5.43, p < .001, d = 1.16$; Turntable task: $t(87) = 17.07, p < .001, d = 3.66$) and decreased looking at the means object (Towel task: $t(110) = 4.38, p < .001, d = 0.84$; Turntable task: $t(109) = 5.25, p < .001, d = 1.01$) in both tasks with age (Figure 2C). Goal-directed behaviors increased in both the towel ($t(88) = 4.34, p < .001, d = 0.93$) and the turntable ($t(87) = 12.56, p < .001, d = 2.69$) tasks across age, while non-goal-directed behaviors decreased in both the towel ($t(87) = 5.35, p < .001, d = 1.15$) and the turntable ($t(86) = 3.45, p < .001, d = 0.74$) tasks (Figure 2D).

Raw data plots showed that the percent of successful trials increased across age for both tasks, with higher success rate observed in the towel task compared to the turntable task throughout the 6–18-month age period (Figure 3). Furthermore, the likelihood of infants' success in the two means-end tasks changed significantly with age. For the towel task, a binomial logistic regression model studying the effect of age on the likelihood of a successful trial outcome was significant: $\chi^2(1) = 47.18, p < .0001$, explaining 18.6% (Nagelkerke R^2 ; Nagelkerke, 1991) of variance in trial success and correctly classifying 72.5% of cases. Hosmer and Lemeshow's test suggested the model was a good fit ($p = .448$). Results suggested that a one-month increase in age made occurrence of success 1.16 times more likely. For the turntable task, a similar logistic regression model was also significant: $\chi^2(1) = 113.6, p < .0001$, explaining 39.4% (Nagelkerke R^2) of variance in trial success and correctly classifying 75.5% of cases. Hosmer and Lemeshow's test suggested the model was a good fit ($p = .368$). A one-month increase in age made occurrence of success 1.25 times more likely.

Detailed information on statistical parameters of the following analyses is provided in online supplementary materials Table S2. Statistically significant differences were found between means-end behaviors performed in successful vs. unsuccessful trials. For the towel task, infants spent more time pulling the towel ($t(22) = 5.28, p < .001, d = 2.25$) and looking at the toy ($t(287) = 8.75, p < .001, d = 1.03$), and less time statically touching the towel ($t(309) = 2.59, p = .010, d = 0.29$) during successful compared to unsuccessful trials; there were no significant differences in other tested behaviors.

For the turntable task, infants spent more time performing alternate ($t(22) = 2.38, p = .027, d = 1.01$) and unidirectional spinning ($t(22) = 5.45, p < .001, d = 2.32$) of the turntable and looking at the toy ($t(22) = 5.12, p < .001, d = 2.18$), and less time statically touching the turntable ($t(301) = 3.98, p < .001, d = 0.46$) and reaching for the toy ($t(301) = 2.87, p = .004, d = 0.33$) during successful compared to unsuccessful trials. These differences were consistent throughout the study.

Infants spent more time performing goal-directed behaviors (Towel task: $t(22) = 5.68, p < .001, d = 2.42$; Turntable task: $t(22) = 7.80, p < .001, d = 3.33$) and less time performing non-goal-directed behaviors (Towel task: $t(287) = 3.19, p = .002, d = 0.38$; Turntable task: $t(301) = 4.02, p < .001, d = 0.46$) during successful as compared to unsuccessful trials in both tasks.

Emergence of Intentionality in Means-End Problem Solving.—Estimated statistical models (see Table S1 in online supplementary materials) suggested that infants started performing more goal-directed than non-goal-directed behaviors at the age of 6.4 months in the towel task. This shift was observed at 10.1 months in the turntable task, suggesting that intentionality might develop sooner in the towel task than the turntable task.

To test that the performance of more goal-directed behaviors during Toy Trials reflected infants' intentionality, we used No-Toy Trials as a control. Detailed information on statistical parameters of the following analyses is provided in online supplementary materials Table S3. Infants' behaviors differed significantly between the Toy and No-Toy Trials. In the towel task, in the presence of the toy, infants spent less time statically touching the towel ($t(306) = 5.25, p < .001, d = 0.60$) and more time pulling the towel ($t(306) = 12.67, p < .001, d = 1.45$) (Figure 4A). In the turntable task, the presence of the toy resulted in less time spent statically touching the turntable ($t(195) = 5.08, p < .001, d = 0.73$) and more time spent in alternate ($t(195) = 2.19, p = .030, d = 0.31$) and unidirectional spinning of the turntable ($t(195) = 4.91, p < .001, d = 0.70$) (Figure 4B). These differences were consistent throughout the study duration. Visual attention towards the means object dropped on average 22.7% (29.6 to 6.9%) between No-Toy and Toy Trials for the towel task ($t(308) = 12.97, p < .001, d = 1.48$) and 32.5% (41.9 to 9.4%) between No-Toy and Toy Trials for the turntable task ($t(219) = 18.25, p < .001, d = 2.47$), and stayed consistent across the 9 to 24 month age period.

In the presence of the end object, with age infants spent more time performing goal-directed behaviors (Towel task: $t(200) = 12.58, p < .001, d = 1.78$; Turntable task: $t(196) = 5.37, p < .001, d = 0.77$) and less time performing non-goal-directed behaviors (Towel task: $t(221) = 11.55, p < .001, d = 1.55$; Turntable task: $t(217) = 7.89, p < .001, d = 1.07$) in both tasks (Figure 5). In the presence of the end object, a point was observed where infants shifted from performing mostly non-goal-directed behaviors to predominantly goal-directed behaviors (suggesting intentionality). A similar shift was not observed for No-Toy Trials in the towel task throughout the 6–24 month age period, or in the turntable task until the age of about 24 months (Figure 5).

Transfer of Knowledge in Means-End Problem Solving.—The likelihood of infants' success in a means-end trial differed significantly between the two tasks. The logistic regression model studying the effect of task on the likelihood of a successful trial outcome was statistically significant: $\chi^2(1) = 47.42, p < .0001$, explaining 37.7% (Nagelkerke R^2) of variance in trial success and correctly classifying 74.5% of cases. Hosmer and Lemeshow's test suggested that the model was a good fit ($p = .671$). The odds of succeeding during the towel task were 4.40 times higher than those for the turntable task across the duration of the study.

The prevalence of goal-directedness in the towel task preceded that demonstrated in the turntable task in 100% of the infants. Of the infants who performed more goal-directed than non-goal-directed behaviors during the towel task, only 20.0% showed a similar level of goal orientation at 6 months in the turntable task, this number increased to 53.8% at 9 months, 55.0% at 12 months, 81.0% at 18 months, and 90.5% at 24 months. Thus, starting at

9 months, the majority of infants seemed to transfer their means-end problem-solving knowledge from the towel task to the turntable task.

Discussion

This study was innovative because it was the first to evaluate the developmental trajectories of behaviors performed by typically developing infants in two means-end tasks, to establish the timeline for the emergence of intentionality in the two tasks, and to determine whether infants demonstrated any transfer of knowledge between the two means-end tasks throughout the first two years of life. The longitudinal design of this study provided a comprehensive picture of means-end problem-solving learning in infancy.

Development of Means-End Problem Solving

As expected (Willatts, 1984a, 1984b, 1999), infants in this study displayed a wide range of visual and manual exploratory behaviors toward the means and end objects in the two means-end tasks from 6 through 24-months-old. Daily, infants actively explore objects using multiple modalities (e.g., proprioceptive, somatosensory, visual, tactile, and oral). This rich exploration provides rich opportunities to learn and understand object affordances, relations among objects, differences between means and end objects, the concept of support, and means-end causation, all important precursors for successful means-end problem solving (Bremner, 2000; Gibson, 1988; Lobo & Galloway, 2008, 2013b; Lobo, Galloway, & Savelsbergh, 2004; Sommerville, Hildebrand, & Crane, 2008; Sommerville & Woodward, 2005a; Sommerville, Woodward, & Needham, 2005; Willatts, 1999). Active exploration can allow for a 'trial and error' process through which infants learn to eliminate behaviors that do not lead to a desired goal (i.e., end object attainment) and to repeat behaviors that are likely to result in reaching the goal. With learning, a shift from more non-goal-directed behavior to predominantly goal-directed behavior would be expected.

Indeed, we found that as infants got older, they engaged in more goal-directed behavior and less non-goal-directed behavior for these tasks. For example, infants increased looking at the end object and decreased looking at the means objects with age. They also increased goal-directed towel pulling and turntable spinning and decreased performance of behaviors that would not result in attainment of the end object, such as static touching, mouthing, lifting, and banging of the means objects. Successful trials in both tasks across all ages were characterized by more goal-directed behavior, and unsuccessful trials were characterized by more non-goal-directed behavior. Therefore, the observed shift towards more goal orientation with age was accompanied by a greater rate of success in both tasks.

Emergence of Intentionality in Means-End Problem Solving

The timing of emergence of intentionality differed between the two means-end tasks even though they both required an understanding of the relational concept of support. Most infants expressed intentionality at the age of 6.4 months in the towel task but not until the age of 10.1 months in the turntable task. The predominant performance of goal-directed behaviors was not observed throughout the first two years of life in control No-Toy trials where an end object was not present. This confirmed that infants' increase in goal-directed

behavior during Toy Trials likely represented the emergence of intentionality in means-end problem solving (Willatts, 1984a, 1999). Manual exploration of the means object coupled with visual observation of the effects on the end object may help young infants develop a means-end concept, so they can conceive and implement a correct sequence of actions (Bower & Wishart, 1972; Diamond, 1991) and also acquire “insight into agency” as they begin understanding the possible consequences of their own actions (O’Connor & Russell, 2015).

In the current study, we observed a steady increase in infants’ goal-directedness in means-end problem solving with age, suggesting no regressions in the development of intentionality. Although understanding of means-end causality emerges gradually via active trial-and-error learning, we aimed to identify a time frame when infants’ behavior became more goal-directed. Different timelines for the emergence of intentionality in the two means-end tasks suggest context-dependency of means-end causal knowledge. As infants acquire *general* understanding about means-end relations, they may still need *specific* practice to be able to implement this knowledge in a new setting or task.

Transfer of Knowledge in Means-End Problem Solving

The earlier appearance of intentionality in the towel task suggested it was easier for infants to solve than the turntable task. Furthermore, we found that the percent of successful trials at the age of 6 months was 3.3 times higher in the towel task than in the turntable task (43.1 vs. 12.9%). Across age, the odds of succeeding were 4.4 times higher in the towel task than in the turntable task. However, learning in the turntable task had a steeper trajectory than that in the towel task: one-month increase in age made occurrence of success 1.16 times more likely in the towel task and 1.25 times more likely in the turntable task. This resulted in similar success rates in both tasks by the age of 24 months (89.4% in the towel task, 91.9% in the turntable task).

Why would the turntable task be more difficult than the towel task, taking into account that both tasks require a seemingly similar understanding of the concept of support and means-end relations? The main distinction between the two tasks was that they required different motor actions to achieve the end goal: pulling vs. rotation of the means object. One might argue that the turntable task may be more difficult for infants because they struggle with understanding the relations between rotational surfaces and the objects they support (Bai & Bertenthal, 1992; Goldfield & Dickerson, 1981).

Moreover, infants’ daily experiences may impact their ability to succeed in the two means-end tasks. For example, current results suggested that at the age of 6 months, pulling the towel occurred 30% of the observation time, while turntable rotation occurred only 6.7% of the time. Only after 9 months of age did infants begin performing rotation of the turntable more than other non-goal-directed exploratory behaviors, such as touching, pulling, banging, and mouthing the turntable. However, even by 24 months, a gap between the amount of towel pulling (72%) and turntable rotation (61.8%) remained. We propose that the difficulty of the turntable task may stem from the comparative novelty of this task for infants: in everyday life, infants are more likely to encounter and explore objects that afford pulling rather than rotation.

Furthermore, by the age of 9 months, the majority of infants who engaged in primarily goal-directed behavior in the towel task also performed mostly goal-directed behavior in the turntable task. We propose that by this age, infants might begin understanding the relations between the means and the end object, comprehending the consequences of their own actions on the objects and generalizing that knowledge across tasks. While the turntable task is more difficult for infants to solve, it does not appear to be more physically demanding. Rather, the turntable task may be more challenging for infants to understand the affordance of the means object and the relation between the means and the end object (Bai & Bertenthal, 1992; Goldfield & Dickerson, 1981). However, by the age of 9 months, infants might be able to transfer their causal knowledge about pulling a support to obtain a toy to the situation of rotating a surface to obtain a toy.

Infants' active exploration facilitates their understanding of means-end causal relations between objects (Lobo & Galloway, 2008; Sommerville, Hildebrand, & Crane, 2008; Sommerville & Woodward, 2005a) and gradually improves their ability to transfer this knowledge across different situations and tasks (O'Connor & Russell, 2015). Although one might hypothesize that means-end understanding appears separately in different, yet related tasks, rather than being transferred from one task to another, it is more likely that infants not only learn to understand means-end relations in *specific* situations, but also acquire the ability to *generalize* that knowledge across related contexts.

Limitations of the Study

The longitudinal design of the current study resulted in infants being tested multiple times in the two means-end tasks. With repetitive testing, it was possible that infants would remember their experience and work upon this knowledge between consecutive testing sessions. Indeed, previous research has shown that active exploration of the objects involved in means-end tasks and their relations can improve infants' means-end problem-solving (Abravanel & Gingold, 1985; Provasi, Dublon, & Bloch, 2001; Sommerville et al., 2008; Sommerville, Woodward, & Needham, 2005). However, as infants' knowledge about means-end causal relations does not emerge in the vacuum, but rather is a direct result of their everyday exploration of objects (e.g., Gibson, 1988), remembering past experiences with means-end tasks is an important part of learning to problem-solve. The non-independent data obtained across the multiple observations were appropriately analyzed in this study using multilevel hierarchical modeling.

The data did not support the performance of statistical testing to support the idea of knowledge transfer between the two means-end tasks at a particular age. Instead, we based our conclusions on the fact that the majority of infants performed a greater amount of goal-directed behavior in both tasks, and that they always succeeded first in the towel task prior to the turntable task. Future research should further investigate this topic using experimental designs.

Conclusions

This longitudinal study provides a more comprehensive picture of the behaviors infants perform with objects as they learn means-end relations. These results highlight that: 1) early

learning often begins with the performance of a greater range of exploratory behaviors that become more refined and goal-directed with age and successful performance; 2) the constraints of tasks may influence infants' level of success and the emergence of intentionality, even when the tasks require an understanding of similar relational concepts; 3) infants may begin to transfer knowledge of support relations between tasks within the first year of life, with most infants showing success in pulling and rotating tasks by 24 months of age. Future research should further explore the issue of generalizability versus specificity in the development of means-end knowledge.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
The Toy Trial setup for the towel (A) and turntable (B) tasks.

Figure 2.

Estimated growth curves for manual behaviors in the towel (A) and turntable (B) tasks, visual attention in the two tasks (C), and goal-directed vs. non-goal-directed behaviors in the two tasks (D); Spinning = unidirectional spinning of the turntable; TW = towel task; TT = turntable task.

Figure 3.
Percent of successful trials across age in the towel and turntable tasks.

Figure 4.

Estimated growth curves for manual behaviors in the towel (A) and turntable (B) tasks in trials with and without the end object; Toy = Toy Trials; No-toy = No-Toy Trials; Spinning = unidirectional spinning of the turntable.

Figure 5.

Estimated growth curves for the goal-directed and non-goal-directed behaviors in trials with or without an object present for the towel task (A) and the turntable task (B); note that in contrast to Figure 2D, goal-directed behaviors in Toy Trials here do not include *Looking at the toy* to ensure unbiased comparison to the No-Toy Trials; Toy = Toy Trials; No-toy = No-Toy Trials.