The emergence of a novel representation from action: evidence from preschoolers

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Abstract

Recent work in embodied cognition has proposed that representations and actions are inextricably linked. The current study examines a developmental account of this relationship. Specifically, we propose that children’s actions are foundational for novel representations. Thirty-two preschoolers, aged 3.4 to 5.7 years, were asked to solve a set of simple gear-system problems. Participants’ motions and verbalizations were coded to establish the strategies they used. The preschoolers initially solved the problems by simulating the turning and pushing of the gears. Subsequently, most participants discovered a new representation of the problems: the turning direction of the gears alternates. Results show that the number of actions that embodied alternation information, during their simulation of the system, predicted the later emergence of the higher-order representation (i.e. that the gears alternate turning direction). Thus, it appears that the preschoolers discovered a new representation based on their own actions. These results are consistent with the developmental embodiment hypothesis: actions are central to the emergence of new representations.

Introduction

The development of new representations is a central problem for theories of knowledge acquisition. Recent work has shown that children, including young infants, have the ability to form abstract representations of relationships in their environments (Casasola, Cohen & Chairello, 2003; Needham, Cantlon & Ormsbee Holley, 2006). For example, Casasola et al. found that infants as young as 6 months old were able to form an abstract categorical representation of spatial relations when presented with a containment task. Using a habituation paradigm, Casasola et al. showed that infants were able to distinguish between a containment relationship (one object fitting within another) and a support relationship (one object placed on top of another). Infants were also able to generalize their representation of containment across different objects and experimental methods. This work demonstrates that even young children have the ability to create abstract categorical representations from relationships they experience.

A complementary line of research with older children has explored the microgenetic processes involved in representational change. Pine and Messer (2000) investigated children’s representation of balance beams in a problem-solving paradigm. On a pre-test, 6- to 9-year-old participants were asked to balance different types of beams (i.e. symmetrical or asymmetrical) one at a time on a fulcrum and explain their solutions to the problems. The central manipulation was whether children simply observed the experimenter solving each balance-beam problem or were additionally asked to explain the experimenter’s solution. They found that children were more likely to change to a higher-level representation in the observe-and-explain condition. Pine, Lufrkin and Messer (2004) suggested that this improvement in performance for the observe-and-explain group was mediated by whether or not children’s gestures during the task mismatched their verbalizations. They noted that children in the observe-only condition also made improvements between the pre-test and the post-test if they had discordant verbalizations and gestures. By analysing the gestures children made while performing and observing the task, Pine et al. provided important evidence for the role of gestures in representational change.

This connection between gestures, or a child’s action, and new strategies may be a crucial element for understanding the process by which representational change occurs. It seems clear that gestures are not simply a nonverbal manifestation of verbal thoughts: children’s verbalizations about their strategy choice do not map directly to the strategy their gestures demonstrate (Alibali & Goldin-Meadow, 1993; Church, Kelly & Lynch, 2000; Perry, Church & Goldin-Meadow, 1992). At a minimum, to the degree that gestures embody...
environmental relationships, they create multimodal redundancy about them. Bahrick, Lickliter and Flom (2007) reviewed evidence that intersensory redundancy supports learning new properties of objects. An understanding of the role that gesture plays in representational change should have deep implications for theories of cognitive development, as well as for theories of embodied cognition. From the perspective of some major approaches to embodied cognition (e.g. Glenberg & Kaschak, 2002), actions are not simply a by-product of cognition – they provide the foundations for representation (Hostetter & Alibali, 2008; Sommerville & Decety, 2006; Thelen, Schoner, Scheier & Smith, 2001; Trudeau & Dixon, 2007).

For example, Kaschak and Glenberg (2000) proposed that objects and relations are represented by the patterns of activation they elicit in the sensorimotor system. A considerable body of evidence now supports this hypothesis (Fischer & Zwaan, 2008). Glenberg and Kaschak (2002) demonstrated that the comprehension of a sentence that implied movement (towards or away from the body) was either facilitated or inhibited depending on its compatibility with the action required to make a ‘yes’ or ‘no’ response (i.e. the ‘yes’ and ‘no’ response buttons were placed such that they required movement towards or away from the body). Participants were faster to respond when there was action–sentence compatibility than when their actions were incongruous with the implied action of the presented sentence. The representations of ‘towards’ and ‘away from’ that participants accessed in order to understand the sentences appear to have been related to their real-time, physical actions (see also Ellis & Tucker 2000; Zwaan & Taylor 2006).

The idea that action and cognition are linked is, of course, not new in developmental theory. For example, Piaget (1954) proposed that knowledge is constructed through actions and it is these actions that lead to the creation of mental representations (see Beilin & Fireman, 2000). A growing body of work in developmental science now suggests that the link between action and cognition may be much as Piaget proposed (see Rakison & Woodward, 2008).

**Actions and the emergence of new representations**

If representations are grounded in actions, then during the emergence of a new representation, actions should play a critical role. More specifically, the performance of actions that provide the basis for a new representation should predict its emergence. In the current study, we capitalize on previous research that has demonstrated a predictive relationship between participants’ actions and the discovery of a new representation. These studies have shown that grade-school and college students spontaneously discover a new way of representing a physical system during problem solving (Dixon & Bangert, 2002; Dixon & Kelley, 2006, 2007). Dixon and Bangert asked participants to solve gear-system problems, namely to predict the turning direction of the final gear in a series, given the turning direction of the first gear (see Figure 1). Most participants initially solved the problems, which were presented as static drawings on a computer screen, by manually tracing the force across the system, based on the simple physics of the gears (i.e. the gears turn and their interlocking teeth push on each other). We call this simulation of the pushing and turning of the gears ‘force-tracing’. Many participants subsequently discovered that the gears form an alternating sequence – adjacent gears turn in opposite directions. The discovery of alternation marks a new representation of the gear problem; this higher-order relationship among the gears is used to solve the problem (Lehrer & Schauble, 1998; Schwartz & Black, 1996).

Dixon and Bangert (2002) found that concentrated use of force-tracing predicted the discovery of alternation. Importantly, performing the force-tracing strategy creates information about alternation, because the participant’s movements alternate turning direction from gear to gear, as a consequence of simulating the force. Note that the gears themselves did not physically move on the computer screen, and thus the only source of information about alternation was the participant’s own actions. Hostetter and Alibali (2008) suggested that gestures emerge from embodied simulations of actions and perceptions; in our study, participants’ use of force-tracing creates a simulation of the physical forces of the gear system. Previous work has shown that repeated use of this force-tracing simulation creates further information about the system, specifically that the gears turn in alternating directions, and thus leads to the discovery of the new, higher-order representation (Dixon & Kelley, 2006).

A limitation of previous research is that grade-school and college students presumably have considerable prior experience with alternation in other domains, and therefore they may have transferred the concept of alternation to the gear domain. In the current study, we extend the gear paradigm to preschool children, because their discovery of alternation is unlikely to reflect transfer. Compared to older children and adults, preschoolers have limited prior experience with systems that alternate; indeed, their skills with early forms of alternating behaviour, such as turn-taking in play and conversation, are still developing (Black & Logan, 1995; Peskin & Ardino, 2003). Furthermore, a large body of work also shows that preschool children rarely transfer deep structural relations, such as alternation, across domains spontaneously (Chen & Klahr, 2008; Lowenstein & Gentner, 2005; Ratterman & Gentner, 1998; Schwartz, Varma & Martin, in press; Tunteler & Resing, 2007). Thus, preschoolers’ discovery of alternation is very unlikely to reflect transfer from another domain. Eliminating, or at least greatly reducing, the viability of transfer as an explanation is important, because it suggests that if alternation is observed, it must be emerging from children’s current interactions.
In summary, the current study investigates a developmental aspect of the embodiment hypothesis by addressing the role of action in the emergence of new representations. This work extends a well-established link between action and new representations, based on evidence from older children and adults, to preschoolers (Dixon & Kelley, 2006, 2007). Because preschoolers have more limited knowledge of alternation, and rarely transfer deep structural relations, their discovery of alternation seems likely to reflect the emergence of new knowledge, constructed in the moment. Thus, a unique contribution of the current study is that it tests a predicted link between action and new representation in a population that has not yet developed the ability or relevant knowledge structures to support transfer.

Specifically, we predict that children as young as 3 to 5 years of age will discover the alternation relationship, just as grade-school and college students did. Furthermore, we expect that, because force-tracing actions create information about the alternating nature of the system, the number of force-tracing actions made prior to discovering this higher-order relation will predict the early generalization of alternation. That is, the quality of the alternation representation should depend on the amount of force-tracing on which it is based. Thus, the rate at which alternation is extended to new problems should depend on the number of force-tracing actions.

Method

Participants

Thirty-two preschoolers, aged 3.4 to 5.7 years, $M = 4.5$ years, $SD = .61$, participated in this study. There were 16 male and 16 female participants. Participants were recruited from local day cares in the northeastern United States.

Procedure

Participants were first familiarized with two properties of gears: gears turn and their interlocking teeth push on one another. The familiarization phase took place using physical, toy gears. A single gear was first used to demonstrate turning, and then two interlocking gears were used to illustrate that teeth push on each other. The two gears were placed perpendicular to one another, so as not to demonstrate that they alternate direction. See the left panel of Figure 2.

After the familiarization phase, each participant was asked to solve a series of 40 gear-system problems as part of a computerized train race, spread across two sessions of 20 trials each. Sessions were separated by no more than two days. The train race was programmed in SuperCard 4.0 and ran on a Macintosh PowerPC. The task was presented on a 17-inch touch-screen monitor. See the right panel of Figure 2.

Figure 1. Examples of types of gear systems used in the experiment. The first gear in the sequence, the driving gear, turned clockwise as indicated by the single arrow. Participants were asked to predict the turning direction of the target. They responded by touching the chute to indicate in which direction they thought the fuel would fall. The gear systems varied in both size and the presence of an extraneous gear.
The problems for the first four trials in each session were presented in a fixed order using simple systems (i.e., small systems with no extraneous gear), whereas the remaining trials were randomized and included more complex systems. We used a fixed order for the first four trials in order to initially present simple systems with final gears that turned both clockwise and counterclockwise. Pilot work showed that children were sensitive to incidental regularities in the early trials (e.g., to successive gears systems turning in the same direction).

For each trial, a static image of a gear system was presented. Participants were asked to decide which way they thought the final gear would turn. The driving gear was always green and was shown with an arrow indicating that it turned clockwise. Each system also included a red final gear, which was called the fuel gear. A small shelf located on the centre of the final gear held fuel for the participant’s train. When the red gear turned, the fuel appeared to fall down a chute on the left or right side of the shelf. Participants indicated which way they thought the fuel would fall by touching the appropriate chute, which positioned their train to catch the fuel.

Each gear system contained a variable number of blue gears that connected the driving gear to the fuel gear. Two arrows appeared on the face of each blue gear. Participants could touch the arrows to indicate the turning direction of the gear. Touching the arrow caused it to turn red and the opposite arrow to dim. The systems contained between two and seven gears. In half of the systems, one of the blue connecting gears was extraneous, that is, it did not affect the outcome. Figure 1 shows examples of the different types of gear systems.

Participants were allowed to change their answer as many times as they wanted prior to making their final decision. After the child made their final decision, all of the gears disappeared except for the fuel gear. The fuel gear then turned in the appropriate direction (based on the physics of the current system), and the fuel then fell into the participant’s train, if they had picked the correct direction, or onto the ground next to the train, if they were incorrect. Correct solutions made their train go faster. A map of the race course was presented to show the participant where their train was in relation to the computer’s train. A final, sham fuelling station was presented after the experimental trials. This station only accepted the correct answer and resulted in every participant winning the race.

**Strategy coding**

We coded each participant’s verbalizations and motions for every gear in each of the 40 systems. All trials were videotaped to allow for reliability coding. Each participant’s motions were coded as clockwise, counterclockwise, left, right, up/down, or pointing. When a participant traced along the edge of a single gear in a circular movement, we coded the motion as ‘clockwise’ or ‘counterclockwise’, depending on the direction of the movement. When a participant pressed one of the directional arrows on one of the intermediate blue gears, we coded it as either ‘left’ or ‘right’, depending on the pointing direction of the arrow. If a participant made a series of connected movements that went from the top of the gear to the bottom of the gear or vice versa (without making a circular movement), repeatedly, it was coded as up/down. We also coded when participants were pointing at a particular gear. These latter categories (i.e., up/down and pointing) were of very low frequency and are not considered further.

Participants were encouraged to think out loud while solving the gear system and to explain how they came to their solution. Verbalizations were coded into eight categories: ‘this way’, ‘that way’, ‘this one’, ‘that one’, ‘left’, ‘right’, ‘counting’ or inaudible.

We used these gear-level codings to quantify the two behaviours of interest: force-tracing and alternation. A force-tracing behaviour was defined as a pair of clockwise–counterclockwise motions made across adjacent gears. Each such pair constitutes a single force-tracing motion. Alternation was defined as the participant either verbalizing a pair of utterances: ‘left – right’, ‘this way – that way’, or ‘this one – that one’, or

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Figure 2  The left panel shows the familiarization phase of the experiment, in which the participants were exposed to the concepts of turning and pushing using physical gears. This picture shows a two-gear system that was used to illustrate the pushing of interlocking teeth. The gears were placed perpendicular to one another so as not to demonstrate alternation. The right panel shows a participant solving a gear system problem presented on the computer screen.
touching a pair of left and right arrows in succession on adjacent gears. Each pair of either verbalizations or motions was considered a single instance of alternation. For example, a child saying ‘left’ and then ‘right’ would be one instance of alternation.

To assess reliability, an independent observer coded 10 randomly selected sessions (200 trials). Agreement with the primary coder was high, 89%.

**Results**

**Accuracy**

Despite the preschoolers’ unfamiliarity with the task, overall accuracy was significantly above chance. Figure 3 shows the cumulative number correct across trials, and the dashed line with the triangles shows chance performance; for example, on trial 10 chance performance is 5 correct trials, whereas on trial 20 it is at 10 correct. As can be seen in the figure, performance in both sessions diverges from the chance line. Here, and in later analyses, we used growth curve analysis to address changes over time. Growth curve analysis is a generalization of multiple regression that naturally handles nested, over-time data (see Singer & Willett, 2003, for an introduction, and Mirman, Dixon & Magnuson, 2008, for extensions to very short time-scales). The model shows that the slope of these lines, \( B = .55 \), is significantly different from the slope of the chance line, \( B = .5 \), \( t(1058) = 3.66 \), but there was no effect of session, \( B = -.005, t(1058) = -.43, p > .65 \). There was no effect of age on accuracy, \( B = -.07, t(1058) = -.15, p > .85 \); alpha was set at .05 for all analyses.

**Response time**

Participants solved the gear problems more quickly during the second session than during the first: for the first session \( M = 24.97 \) seconds, \( SD = 18.24 \), and for the second session \( M = 20.96 \), \( SD = 20.68 \). \( F(1, 1091) = 11.60 \). Furthermore, response time decreased more quickly across trials in the first session, \( B = -.79 \), than in the second, \( B = -.28, t(1058) = 2.09 \). In sum, participants responded more quickly in the second session, and showed greater gains in speed during the first session. There were no effects of age on response time.

**Motions and verbalizations**

The key predictions in this study concern the relationship between force-tracing motions and participants’ later use of alternation. Recall that force-tracing motions were defined as pairs of clockwise and counterclockwise movements on adjacent gears. Alternation was defined as verbalizing a pair of utterances, ‘left – right’, ‘this way – that way’, ‘this one – that one’, on adjacent gears, or touching the left and right arrows in succession on adjacent gears. Overall, 27 participants (84%) used at least one force-tracing motion, and 25 (70%) performed at least one alternation behaviour during the experiment. In total, the participants made 334 force-tracing motions. They also engaged in a considerable amount of alternation behaviour: 159 verbalizations and 1065 motions. Figure 4 shows the distribution of force-tracing motions, alternating motions, and alternating verbalizations scaled by the number of gears in the system (e.g. number of force-tracing motions/number of gears in system). Scaling simply adjusts for the fact that more motions and verbalizations would be expected for larger systems. Force tracing, in both sessions, starts out near its highest levels and then decreases significantly over trials, \( B = -.007, t(1058) = -2.71 \). In contrast, alternation behaviour increases over trials, \( B = .005, t(1058) = 2.23 \). For this analysis and those that follow, we considered alternation motions and verbalizations as a single category (i.e. alternation behaviour), because they were indicative of the same concept and the number of verbalizations was too small to support separate analyses.

There was a significant difference in accuracy between trials on which alternation behaviour occurred (at least once) and those without alternation, \( M = .64 \) and .54, respectively. \( F(1, 1115) = 7.90 \). Furthermore, within those trials on which alternation occurred one or more times, we found that greater amounts of alternating behaviour were significantly related to accuracy, although the relationship was modest, \( r(220) = .16 \). Consistent with previous work with older children and young adults, the use of alternation is associated with

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**Figure 3** The cumulative number of correct answers is shown as a function of trials. The dashed line shows chance performance, and the solid lines show performance for sessions 1 and 2.
greater accuracy. There were no significant effects of alternation behaviour on response time.

**Force-tracing predicts the development of alternation**

We proposed that force-tracing creates information about alternation and, therefore, that the number of force-tracing motions should predict the subsequent growth of alternation. To test this hypothesis, we modelled the increase of alternating behaviours as a function of the amount of force-tracing made prior to the participant’s first alternation behaviour. As predicted, the number of prior force-tracing motions moderated the rate of change in alternation, \( B = .0003, t(759) = 2.13 \). Participants who had used more force-tracing had faster rates of growth in their production of alternating behaviours, consistent with the hypothesis that force-tracing creates the information relevant for this new representation of the gear system. Figure 5 illustrates this relationship; participants are grouped into high or low force-tracing, depending on how much force-tracing they performed prior to their first use of alternation (split at the median value). As can be seen in the figure, the high-force-tracing group uses alternation increasingly across trials. (The analysis captures this relationship more comprehensively because it treats force-tracing continuously.) The high variability in the use of alternation is consistent with previous work on the generalization of new strategies after discovery (Siegler, 2007). Immediately after the discovery of a new strategy, children often vacillate between the old and new strategies.

**Discussion**

We found that, like older participants, preschool children spontaneously discovered the alternation relationship as they interacted with the gear system. The switch to using alternation is of interest, not only because it is evidence of a shift to a new representation, but also because participants’ use of the alternation behaviour was associated with increased levels of accuracy. Creating this new representation of the gear system demonstrably improves performance. Most importantly, we found that the number of force-tracing motions a participant made predicted their subsequent use of alternation. Participants who had used more force-tracing, prior to discovering alternation, expanded their use of alternation more rapidly on later problems. This result is consistent with the hypothesis that performing the force-tracing strategy grounds the representation of alternation, because the actions created by force-tracing embody the higher-order alternation relationship. Thus, the current results provide support for a developmentally important prediction from work on embodiment: new representations are grounded in action.

We note that the force-tracing strategy is the joint product of children’s understanding of the simple physics of the system (e.g. gears turn, interlocking teeth push) and...
the properties of the gear-system task (i.e. the gears are aligned on a single plane). Simulating the turning and pushing of gears on a two-dimensional plane results in the force-tracing strategy. As the force-tracing strategy is performed on individual gears and gear-to-gear junctions, it creates a pattern of alternating motions at a longer timescale (Dixon & Kelley, 2006). It is worth highlighting that the display itself contains no alternating elements, nor do the gears themselves ever move in an alternating pattern. The only source of information about alternation is created by the participants’ own actions. [The pattern created by children touching the arrows (arrowheads become highlighted when touched) might be considered a source of perceptual information, but this pattern is created by the child’s actions. Furthermore, for the current analyses, touching two arrowheads, so as to create an instance of alternation, was coded as an alternation behaviour. The predictors (i.e. force-tracing) are all derived from trials prior to the first instance of any alternation behaviour.] Schwartz and Black (1996) provided an even more extreme example of this phenomenon by verbally presenting gear problems to tenth- and eleventh-grade students without any graphical depiction. Parallel to the findings presented here, their results suggested that force-tracing was a precursor to alternation.

Here, as in previous work, we have shown that force-tracing predicts the future emergence of alternation as a new representation of the problem. Children (and adults) stop simulating the movement and forces in the system, and begin treating the gears as an alternating sequence. However, in contrast to previous work, the current analyses have essentially zoomed in to a finer grain by examining the relationship between the number of force-tracing actions and the later growth of alternating behaviours, rather than classifying behaviour at the level of individual trials. This finer-grained analysis, a unique contribution of this study, allows us to see how the early growth of the alternation representation is related to previously performed actions.

The current study also extends previous work by showing that preschool children can acquire the alternation relationship, just as older participants do. Preschoolers are still developing their skills with even the most rudimentary alternation relationships – those involving two agents, such as turn-taking in play and conversation (Tremblay-Leveau & Nadel, 1995). It would be very surprising if they could extend these developing concepts to a domain that was extremely dissimilar in terms of its surface features and that involved multiple elements (see Chen & Klahr, 2008). The likelihood that their use of alternation reflects transfer from another domain should be very low. Given that transfer is unlikely, we suggest that preschoolers may be creating the alternation relation de novo, without reference to another domain. Of course, it is not possible to completely rule out transfer as a potential explanation for the observed results. For example, one might hypothesize that making alternating actions somehow creates structural alignment with previous knowledge from some domain. Thus, an additional contribution of the current study is that it offers preliminary, but not conclusive, evidence that actions may be central to the generation of representations of new relationships.

Given that the current study was the first extension of the gear paradigm to this very young age group, our strategy was to measure the behaviour of interest, force-tracing, at a fine grain, rather than to manipulate it. However, in previous work with college students, Dixon and Dohn (2003) experimentally manipulated the amount of force-tracing participants used on a structurally analogous task, predicting the movement of interconnected balance beams, and showed that the amount of force-tracing affected their representation of alternation. Participants in the high-force-tracing condition transferred alternation to the gear task more quickly and generalized it more robustly than did their counterparts in the no-force-tracing (experiment 1) and low-force-tracing (experiment 2) conditions. These experiments suggest a causal relationship between force-tracing actions and the representation of alternation.

More recently, Cook, Mitchell and Goldin-Meadow (2008) manipulated whether third- and fourth-grade children gestured while learning a new mathematical problem (i.e. equivalence: 4 + 3 + 6 = _ + 6). They found that requiring or preventing gesture during the introduction to the problems affected participants’ retention on a follow-up test given four weeks later, demonstrating that gesturing may play a causal role in knowledge acquisition.

The current results, taken with these previous experimental findings, suggest that new representations may emerge from actions. A fundamental challenge for developmental theories is to explain how new structures emerge from current structures. Representations, as cognitive structures, are presumed to emerge from interactions with the environment. Embodied approaches to cognition are potentially important for understanding how this might occur, because they propose that actions are the foundations of representation (and actions are by definition interactions with the environment). Actions, on this account, are not simply a byproduct of cognition; rather, they play an integral role in the process of creating representations.

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References


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