Research Article

INDIVIDUATION OF ACTIONS FROM CONTINUOUS MOTION

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Abstract—*Three studies explored how infants parse a stream of motion into distinct actions. Results show that infants (a) can perceptually discriminate different actions performed by a puppet and (b) can individuate and enumerate heterogeneous sequences of such actions (e.g., jump-fall-jump) when the actions are separated by brief motionless pauses, but (c) are not able to individuate such actions when embedded within a continuous stream of motion. Combined with previous research showing that infants can individuate homogeneous actions from an ongoing stream of motion, these findings suggest that infants can use repeating patterns of motion in the perceptual input to define action boundaries. Results have implications as well for infants' conceptual structure for actions.*

The human mind seems built to create distinct units from continuous input. Humans parse objects from a continuous surface layout, speech from a continuous sound stream, and distinct actions from continuous motion. Some of these abilities develop quite early: There is considerable evidence showing that young infants parse their surroundings into distinct objects, and expect these objects to endure over time and behave in predictable ways (e.g., Spelke, 1988, 1991). Similarly, soon after birth, infants already parse speech streams into distinct phonemes (e.g., Marean, Werner, & Kuhl, 1992).

There has been relatively little research, however, investigating infants' ability to parse the ongoing activity of the world around them into distinct actions. Yet clearly this ability is essential. First, at the most fundamental level, it is required to perceive causality. Consider the simplest possible case, the classic launching event in which one object hits a second, stationary object, causing the latter to move. It would be impossible to recover the causality in this sequence if it were not segmented into two distinct actions; the motion would necessarily be perceived as one undifferentiated swoosh.

Second, individuating actions is a necessary precursor to producing them. A child who wants to throw a ball but has not yet realized that pulling back one's arm is a necessary component of the throw, and jumping up and down in excitement afterward is not, will likely have an ineffective throw. Further, once one has individuated actions, one can both perform them separately and recombine them in new and productive ways. Thus, a child who has decomposed the act of tying a shoelace into the distinct actions of tying a knot and making a bow can use those same actions on other items (wrapping a gift with a bow), or use them individually as needed (e.g., tying a knot in a strap so it does not slip).

A third major motivation for parsing motion into discrete actions lies in the need to interpret and explain the behaviors of others. Commonsense folk psychology is founded on the attribution of desires and beliefs; people talk constantly in terms such as "he opened the window because he wanted fresh air," and "she mopped the floor to hide the evidence." Yet beliefs and desires are mental phenomena; an observer must infer these on the basis of manifest behavior. Parsing motion into discrete acts provides both the behavioral units to explain and units that are explainable, that is, coherent. (See, e.g., the extensive literature on scripts: Nelson, 1986; Shank & Abelson, 1977.)

Finally, people must individuate actions in order to communicate effectively with others—and, indeed, in order to acquire verbs at all. For language to be comprehensible, two people must have the same bounded pattern of motion in mind when they refer to a "jump," a "hug," or a "hit."

What cues might infants use to individuate actions? Research in other domains suggests that the constraints of spatial and temporal continuity form a fundamental basis for individuating entities of many kinds. For example, Spelke (1988) has shown that infants construe spatially separated surfaces in the visual layout as belonging to distinct objects. Similarly, Bregman (1990) has demonstrated that portions of acoustic energy that are temporally separated by silence are interpreted by adults as arising from independent acoustic events, whereas energy that is temporally continuous and judged to originate from the same location is frequently interpreted as arising from the same acoustic event.

These facts suggest that infants may use spatiotemporal discontinuities to segment scenes of motion into distinct units: Portions of motion separated by "gaps" in space, time, or both may mark different actions. This hypothesis was recently tested in the only research to date to specifically address infants' ability to individuate actions (Wynn, 1996). In the first study, one group of 6-month-old infants was habituated to a puppet jumping two times on a stage, pausing briefly between jumps; another group was habituated to the puppet jumping three times, again pausing between jumps. After habituation, both groups of infants were presented with two- and three-jump trials. Infants looked reliably longer at trials containing the new number of jumps, showing they had enumerated the jumps (tempo and duration of the sequences were controlled). Because enumeration requires that the counted entities first be recognized as separate entities, this finding also demonstrates that the actions were individuated. In a second study, the boundaries between motion and the absence of motion were removed; the puppet gently wagged its head back and forth between jumps and briefly following the last jump in a sequence. Infants again showed a preference for the new number of actions, showing that a temporal discontinuity in motion per se was not required for infants to detect action boundaries. However, infants in the first experiment discriminated the new number from the old more strongly than did infants in the second study, showing that temporal discontinuity of motion is a useful cue for individuating actions, without being necessary.

The studies reported here explored in further detail how infants parse ongoing motion into discrete actions. One possibility is that infants are sensitive to repeating patterns of motion in the perceptual input. In the study just described, they may have used the repeating perceptual pattern of "up-down motion followed by side-to-side motion" to detect unit boundaries. This possibility is consistent with research showing that infants can detect other abstract regularities in

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input. For example, Canfield and Smith (1996) demonstrated that 5-month-olds can use the number of sequential presentations of a picture in one location to anticipate when a picture will appear in a second location. Even more impressively, Saffran, Aslin, and Newport (1996) showed that 8-month-old infants can use the transitional probabilities between syllables to parse a continuous stream of speech into its constituent parts after only 2 min of exposure, despite the lack of other prosodic cues. It is plausible, then, that infants at this age may detect the regularities in the motion around them and use these regularities in determining action boundaries.

EXPERIMENT 1

This experiment tested infants' ability to perceptually discriminate two kinds of actions, the jumps and falls of a puppet. Only if they have this ability would it be possible to test the repeating-cycles hypothesis by presenting infants with heterogeneous sequences of actions (e.g., jump-fall-jump) that lack such a reiterating pattern.

Method

Subjects

Twenty-two full-term 6-month-old infants participated (mean age = 6 months, 9 days; range: 5 months, 20 days to 6 months, 16 days), with 6 girls and 5 boys in each familiarization condition. Four additional infants were dropped after failing to complete at least four test trials because of fussiness (3 infants) or experimenter error (1 infant).

Apparatus

All events took place on a yellow display stage (55 cm tall, 82 cm wide, and 40 cm deep), against which the black, orange, and white Daffy Duck puppet contrasted strongly. A black curtain was lowered between trials to hide the stage, and additional curtains to the sides kept infants focused on display events. Infants sat in an infant seat 90 cm from the stage; as a result, the 30-cm-high puppet subtended a visual angle of 18°. Two video cameras recorded events for postsession review. Recording of each infant's looking time was done live by an observer who could see the infant but not the display stage.

Design

Infants were shown six familiarization trials in which the puppet performed two actions, with a 0.5-s motionless pause in between the actions.[1] Half the infants saw "jumps," and half saw "falls." On each jump, the puppet rose approximately 6 cm and returned to its point of origin. On each fall, the puppet rotated approximately 75° to the right in the fronto-parallel plane, from a vertical to an almost horizontal position, and then returned to its original orientation. Each action took 1 s to complete. Infants were then presented with six test trials of two actions apiece. Test trials alternated between the novel action and the familiarized action. Order of presentation (old-new and new-old) was counterbalanced across subjects.

Procedure

Prior to testing, informed consent was obtained from subjects' parents, and each infant was shown the puppet and allowed to touch it. Classical music played softly throughout the experiment. Testing began with a brief introduction to the stage and its operations: A gloved hand appeared from above and patted the bottom and sides of the stage, and the curtain was raised and lowered.

For all trials, the curtain was raised to reveal a stationary puppet. Approximately 2 s later, the experimenter began manipulating the puppet to perform the specified actions (either jump-jump or fall-fall) to the beat of a metronome (audible only to the experimenter, who wore earphones). Timing of infants' looking began 0.5 s after the completion of the last action and continued until the infant either looked away from the display for more than 2 s after a minimum look of 0.5 s or reached a cumulative looking time of 30 s. The curtain was then lowered for approximately 2 s before being raised to begin the next trial. There was a break of approximately 20 s in between the familiarization and the test trials; during the break, the infant was turned away from the stage and allowed to interact with his or her parent. All timing in this and the other experiments was done by one of two highly experienced observers.

Results and Discussion

A 2 (familiarization condition: jumps vs. falls) × 2 (sex) × 2 (trial kind: novel vs. familiarized action) repeated measures analysis of variance (ANOVA) on infants' mean looking times showed only a significant effect of trial kind; no other main effects or interactions were significant. Infants looked on average for 4.8 s on trials containing the familiar action and 6.6 s on trials containing the new action, $F(1, 18) = 4.89$, $p < .05$ (see Fig. 1). A nonparametric Wilcoxon Signed Rank Test confirmed the finding: Overall, 15 of the infants preferred the new action at test, and 7 preferred the old ($z = -1.948$, $p = .05$). Thus, infants perceptually discriminated these two kinds of actions.

EXPERIMENT 2

The finding in Experiment 1 allowed us to test whether a repeating pattern of motion is necessary for infants to successfully parse

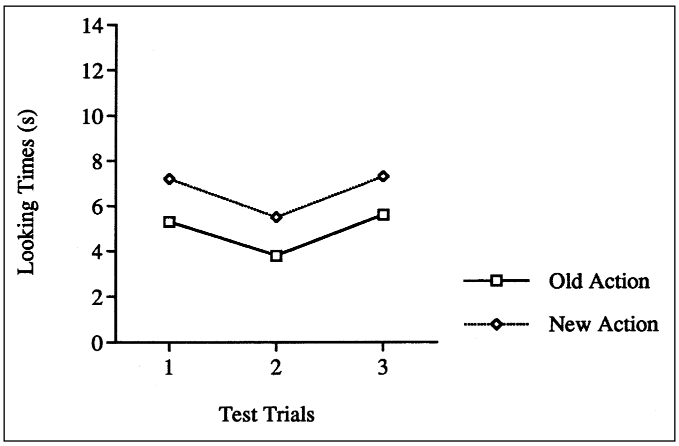

Fig. 1. Infants' looking times to the familiar and new actions in Experiment 1, across the three pairs of test trials.

1. Pilot testing showed that familiarizing rather than fully habituating infants significantly decreased their dropout rate.

Table 1. *Structure of action sequences in Experiments 2 and 3*

Familiarization group	Test sequences matched for . . .	Trial kind	Tempo (inter-action interval in seconds)	Duration of sequence (in seconds)
2 actions	Duration	Familiarization (2 actions)	2	4.5
		Test (2 actions)	3	5.5
		Test (3 actions)	1	5.5
2 actions	Tempo	Familiarization (2 actions)	2	4.5
		Test (2 actions)	1	3.5
		Test (3 actions)	1	5.5
3 actions	Duration	Familiarization (3 actions)	2	7.5
		Test (3 actions)	1	5.5
		Test (2 actions)	3	5.5
3 actions	Tempo	Familiarization (3 actions)	0.5	4.5
		Test (3 actions)	1	5.5
		Test (2 actions)	1	3.5

Note. As a control for the possibility of infants responding in the test trials on the basis of the tempo or duration of the sequences, rather than number, half of each familiarization group received test trials that were matched for a new overall duration, with the tempo of the new-number and old-number test sequences differing equally (one faster, one slower) from that of the familiarized sequences. For the other half of each familiarization group, test sequences were similarly matched for tempo and controlled for duration.

ongoing motion into discrete units. In the next experiment, we familiarized infants with heterogeneous sequences of actions (e.g., jump-fall-jump) that afforded no such cycle. Further, to provide as clear a test as possible, we removed the possibility that infants could simply separate the jumps and falls based on temporal discontinuity by having the puppet move continually in between the actions and briefly following the last action.

Method

Subjects

Thirty full-term 6-month-olds participated (mean age = 6 months, 1 day; range: 5 months, 7 days to 6 months, 16 days). There were approximately equal numbers of boys and girls in each familiarization condition. An additional 17 infants were excluded after failing to complete at least four test trials because of fussiness (9), disinterest (5), sleepiness (1), and experimenter error (2).

Design

Subjects were randomly divided into two groups; one was familiarized to sequences of two heterogeneous actions (jump-fall and fall-jump), and the other was familiarized to sequences of three heterogeneous actions (jump-fall-jump and fall-jump-fall). There were six familiarization trials in total, three of each composition, alternating across trials in an ABAABB order. There were also six test trials, alternating between new and old number of actions. Order of test-trial presentation (new number first or old number first) was counterbalanced across subjects.

To achieve novelty of test sequences, we used test trials consisting of homogeneous sequences (all jumps or all falls; there exist only two possible heterogeneous two-action sequences, both of which were presented in the two-action familiarization trials). As a control for the possibility of infants responding in the test trials on the basis of the tempo or duration of the sequences, rather than number, half of each familiarization group received test trials in which the old- and new-number sequences were matched for overall duration, with the tempo (inter-action interval) of the new-number and old-number test sequences differing equally (one faster, one slower) from that of the familiarized sequences. For the other half of each familiarization group, test sequences were similarly matched for tempo and controlled for duration (see Table 1).

Procedure

The procedure was identical to that of Experiment 1 with the exception of the timing and the content of the sequences, as noted. In addition, we deprived infants of the key cue of motionless pauses between actions by having the puppet rotate approximately 20° back and forth on its vertical axis between actions and for 0.5 s following the last action in each trial. These rotations made the puppet appear to be shaking its head and arms from side to side in a jiggling motion.[2]

Results and Discussion

Figure 2 shows infants' mean looking times to the new versus the familiarized number of actions on the test trials. A 2 (familiarization condition: two vs. three actions) × 2 (control condition: test trials equated for duration vs. tempo) × 2 (sex) × 2 (trial kind: two vs. three actions) repeated measures ANOVA conducted on infants' mean looking times revealed no significant effects or interactions. On average, infants who were familiarized to two-action sequences looked at the two-action test sequences for 5.2 s and the three-action test sequences for 5.4 s; infants familiarized to three actions looked 7.3 s at the two-action test

2. This change in procedure from the wagging motion used in Wynn (1996) was made necessary by the fact that in order to offer a larger repertoire of actions (i.e., jumps and falls), we had to manipulate the puppet by a stem from beneath, instead of a dowel through the beak, as before. It should be noted that to adults, the jiggling and wagging appear quite similar.

sequences and 6.8 s at the three-action test sequences. A nonparametric Wilcoxon Signed Rank Test confirmed the results: Of the infants familiarized to two actions, 7 preferred two actions at test and 8 preferred three ($z = -0.09$, $p > .93$), and of the infants familiarized to three actions, 6 preferred two actions at test and 9 preferred three ($z = -0.68$, $p > .49$).

This result reinforces the possibility that repeating patterns of motion are an important cue to infants in parsing ongoing motion into distinct units. Recall that when presented, under very similar conditions, with a continuous, homogeneous sequence of actions (jumps interspersed with wagging in Wynn, 1996), infants successfully individuated and enumerated the jumps. However, before reaching a final conclusion, we had to rule out an alternative explanation: Infants' difficulty in this experiment might have arisen not with individuation but with enumeration. In other words, their performance may have reflected not problems in individuating distinct actions from a nonrepeating pattern of ongoing motion, but instead problems with enumerating heterogeneous sequences of actions. The next experiment tested this alternative explanation.

EXPERIMENT 3

Infants were again presented with heterogeneous sequences of actions, but the key cue of motionless pauses between actions was restored. Given the importance of spatial and temporal discontinuities to individuation, this manipulation should have been sufficient to allow infants to individuate the actions. In effect, the jumps and falls were "preindividuated," and the task simply became a test of whether infants are able to enumerate a heterogeneous sequence.

Method

Sixteen full-term 6-month-old infants (even numbers of boys and girls) participated (mean age = 5 months, 28 days; range: 5 months, 17 days to 6 months, 17 days). An additional 3 infants were excluded after failing to complete at least four test trials because of fussiness.

Experiment 3 used the same design and procedure as in Experiment 2, except that the jiggling motion between actions was removed, resulting in a motionless pause between actions. As in the previous experiment, timing began 0.5 s after the completion of the last jump or fall.

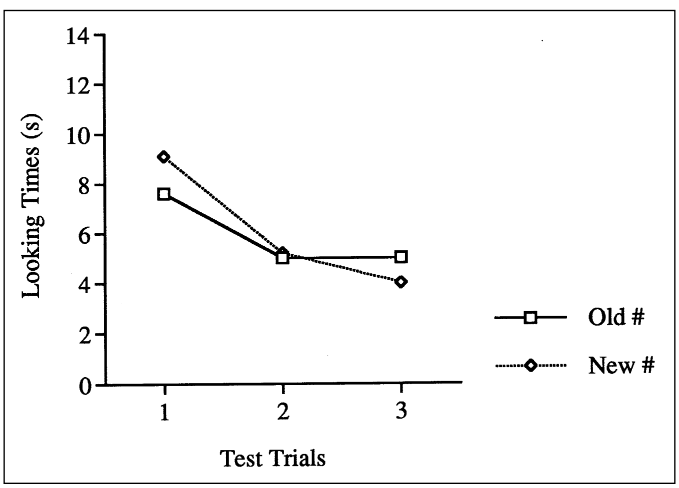

Fig. 2. Infants' looking times to sequences containing the familiarized and new number of actions in Experiment 2, across the three pairs of test trials.

Results and Discussion

Figure 3 shows infants' mean looking times to the new versus the familiarized number of actions on the test trials. A 2 (familiarization condition: two vs. three actions) × 2 (control condition: test trials equated for duration vs. tempo) × 2 (sex) × 2 (trial kind: two vs. three actions) repeated measures ANOVA conducted on infants' mean looking times revealed no significant main effects but two significant interactions. First, there was a Trial Kind × Control Condition interaction, $F(1, 8) = 9.15$, $p < .05$. Infants in the tempo-equated condition looked longer at the two-action than the three-action test sequences (11.8 s vs. 8.1 s, respectively), whereas infants in the duration-equated condition looked longer at the three-action than the two-action test sequences (9.3 s vs. 5.8 s, respectively). Close analysis of Table 1 shows that this result could reflect general preferences for sequences that are quicker, shorter, or both.

More important, there was a significant Trial Kind × Familiarization Condition interaction, $F(1, 8) = 12.94$, $p < .01$. On average, infants who were familiarized to two-action sequences looked at the two-action test sequences for 11.4 s and the three-action test sequences for 7.0 s; infants familiarized to three actions looked 6.2 s at the two-action test sequences and 10.4 s at the three-action test sequences. A nonparametric Wilcoxon Signed Rank Test confirmed the results: Of the infants familiarized to two actions, more preferred two actions at test than three (7 vs. 1, $z = -1.96$, $p < .05$), whereas of the infants familiarized to three actions, more preferred three actions at test than two (6 vs. 2, $z = -1.96$, $p < .05$).

Interestingly, in contrast to the novelty preference often revealed by habituation studies, infants who in this experiment were familiarized to one number showed a strong preference for the same number in the test trials. There are three possible explanations for this finding.

First, infants in our study did not undergo a full habituation; thus, they may still have been actively processing the content of the familiarization trials, which could have led to a heightened interest in test trials with a similar content—in this case, numerical. Research specifically comparing the effects of a fixed-length familiarization with an infant-controlled habituation confirms that with the very same task and materials, a familiarization procedure can produce a familiarity preference whereas a full habituation produces a novelty preference (Hunter, Ross, & Ames, 1982). However, an inspection of the data reveals that the 3 infants who met a habituation criterion in the six familiarization trials (i.e., whose total looking time on the last three trials was less than half of their looking time on the first three trials) all preferred the matching number in the test trials, suggesting that an incomplete-processing account may not fully explain the infants' behavior.

Second, research from certain discrepancy theories shows that a moderate degree of novelty is sometimes preferred over either greater or lesser novelty (Berlyne, 1968, 1970; Kagan, 1971; McCall & McGhee, 1977; see also Slater, Rose, & Morrison, 1984, Experiment 2, for a related finding). The logical constraints of the experiment required that the test trials be homogeneous, necessarily introducing an additional element of novelty. Consequently, test trials offered a contrast between (a) an old number of actions with a switch from heterogeneity to homogeneity of the sequences and (b) a new number with a switch from heterogeneity to homogeneity of the sequences. Discrepancy theory would explain the infants' preference for the matching-number test sequence as reflecting an optimal level of stimulation.

Third, previous research has shown that infants sometimes exhibit a preference for an abstract match between their initial exposure and test (e.g., Meltzoff & Borton, 1979; Spelke, 1981). In our study, infants may have found interesting the numerical correspondence between a heterogeneous action sequence of a given number in the familiarization and a homogeneous action sequence of the same number in the test.

Experiment 3 thus shows that infants have no difficulty enumerating a heterogeneous sequence of actions when provided the boundary cue of temporal discontinuity between actions. This finding disproves the alternative explanation for infants' failure to discriminate the test sequences in Experiment 2: Their difficulty was not in enumeration, per se. Together, the results support the hypothesis that a repeating cycle of motion is in fact an important cue to infants in parsing continuous motion into distinct units.

GENERAL DISCUSSION

These three experiments show that infants can perceptually discriminate single actions, and can individuate and enumerate a sequence of such actions provided that action boundaries are specified by motionlessness. However, they are not able to parse heterogeneous actions from a continuous, nonpatterned stream of motion. In combination with the results of Wynn (1996), this pattern of results suggests that infants make use of a relatively complex perceptual cue for individuating actions: They succeed in parsing a continuous stream of motion into discrete components when the composition of the sequence affords a repeating cycle of motion. Although perfectly viable in certain circumstances, this approach has limited general utility, as most activities do not involve repeating cycles of motion. This raises the possibility that many scenes of everyday activity, such as a parent walking around a room tidying up, may be unintelligible to infants. It may be that infants manage to construct representations of different kinds of actions only after extensive observation of them in repeated sequences or in isolation, and only then succeed in individuating them from a continuous stream of motion. Alternatively, it may be that infants make use of additional cues not examined in our studies, for example, cues to the goals or intention of the actor (Bloom, 1997). Infants may be helped by their emerging understanding of other people as agents who have goals and intentionally perform specific acts to achieve desired goals. The basis for such an understanding is already in place: Recent research has shown that infants at this age are sensitive to movement information specifying social contingencies (Carpenter, Morgan, & Rochat, 1996), have expectations of a hand as a goal-directed agent (Woodward, 1995), and can even determine the intended action of a person from witnessing unsuccessful attempts to perform the action and then successfully imitate the action themselves (Meltzoff, 1995, 1997).

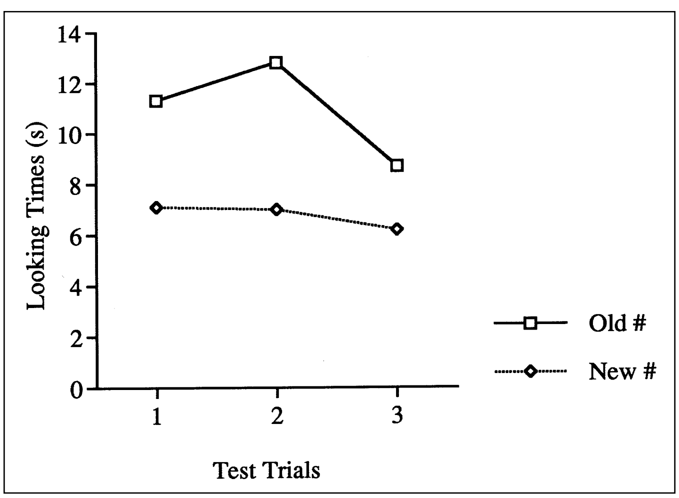

Fig. 3. Infants' looking times to sequences containing the familiarized and new number of actions in Experiment 3, across the three pairs of test trials.

The current findings have implications in another area as well. Recent research on infants' ability to individuate objects suggests that infants are aided by their developing knowledge of object kinds (Spelke, Gutheil, & Van de Walle, 1995). For adults, individuation by categorization is common and effortless. An adult who sees a cow wearing a hat immediately knows that there are two entities, even though they are spatially contiguous, because the adult has a concept of "cow" and a concept of "hat." Similarly, adults watching someone perform a leap followed seamlessly by a bow are aided in the perception of two actions by their concepts of "leap" and "bow." The fact that infants were unable to parse jumps and falls from an ongoing stream of motion suggests that they lack concepts for these basic-level actions.[3]

Such an interpretation would be consistent with studies in the domain of objects: For example, research by Mandler and McDonough (1993) shows that infants possess "global" categories of objects (such as "animal" and "vehicle") before they possess basic-level concepts such as "dog." One interesting possibility is that infants may not begin to develop specific concepts of individuated actions until they learn language. Learning labels for different kinds of action could organize infants' attention and provide the initial entry into the formation of action concepts. This view has been argued by Quine (1981), among others.

The fact that infants enumerated heterogeneous actions within a single count has one further implication for infants' conceptual structure for actions. It is at least conceivable that 6-month-old infants would fail to perceive the ontological similarity across different kinds of actions, and thus fail to conceive of a sequence of disparate actions as a set that can be counted. This would be somewhat analogous to the unnaturalness, for an adult, of enumerating a set composed of three apples and a window. Infants' ability to enumerate the heterogeneous sequences therefore suggests that they possess a concept of "physical action" that provides criteria for individuating and identifying such actions.

Virtually nothing is known about infants' ability to parse the ongoing activity of the world around them into distinct and meaningful parts. The research reported here outlines both some competencies and

3. It is also possible that infants possess these concepts, but their representations are too weak to support individuation from a continuous background. Just as it takes extensive practice for radiologists to learn to detect the boundaries of tumors in x-rays, infants could possess concepts of "jump" and "fall" but have difficulty detecting them in a noisy environment. This is, however, the less parsimonious account.

some limitations; future research is needed to delineate more clearly the role of perceptual, intentional, and linguistic cues in the development of this fundamental ability.

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