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Keeping the end in mind: Preliminary brain and behavioral evidence for broad attention to endpoints in pre-linguistic infants

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ABSTRACT

Infants must learn to carve events at their joints to best understand who is doing what to whom or whether an object or agent has reached its intended goal. Recent behavioral research demonstrates that infants do not see the world as a movie devoid of meaning, but rather as a series of sub-events that include agents moving in different manners along paths from sources to goals. This research uses behavioral and electrophysiological methods to investigate infants' (10–14 months) attention to disruptions within relatively unfamiliar human action that does not rely on goal-objects to signal attainment (i.e., Olympic figure skating). Infants' visual (Study 1, $N = 48$) and neurophysiological (Study 2, $N = 21$) responses to pauses at starting points, endpoints, and within-action locations were recorded. Both measures revealed differential responses to pauses at endpoints relative to pauses elsewhere in the action (i.e., starting point; within-action). Eye-tracking data indicated that infants' visual attention was greater for events containing pauses at endpoints relative to events with pauses at starting points or within-actions. ERP activity reflecting perceptual processes in early-latency windows (< 200 ms) and memory updating processes in long-latency windows (700 − 1000 ms) showed differential activation to disruptions at the end of a figure-skating action compared to other locations. Mid-latency windows (250 − 750 ms), in contrast, showed enhanced activation at frontal regions across conditions, suggesting electrophysiological resources may have been recruited to encode disruptions within unfamiliar dynamic human action. Combined, results hint at broad sensitivity to endpoints as a mechanism that supports infants' proclivity for carving continuous and complex event streams into meaningful units. Findings have potential implications for language development as these units are mapped onto budding linguistic representations. We discuss empirical and methodological contributions for action perception and address potential merits and pitfalls of applying behavioral techniques in conjunction with brain-based measures to study infant development.

1. Introduction

Action flows around us continuously – from the hustle and bustle of city streets to the fluidity and precision of classical ballet. Adults are adept at carving up this continuity to understand, predict, and remember events, yet even infants demonstrate prowess in

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making sense of the 'blooming, buzzing confusion' (James, 1890). Indeed, recent behavioral evidence suggests that infants do not view the world as a movie devoid of meaning but rather as a series of sub-events that include agents moving in different manners along paths from sources to goals (Göksun, Hirsh-Pasek, & Golinkoff, 2010; Levine, Buchsbaum, Hirsh-Pasek, & Golinkoff, 2019), and that infants' initial event representations may be important as they learn language that maps onto the components and patterns within those events (Bauer, 1992; Friend & Pace, 2011; Konishi, Stahl, Golinkoff, & Hirsh-Pasek, 2016). The present article builds upon infant's established sensitivity to goal-related information within dynamic human action, using both behavioral and neurophysiological methodologies to test whether infants' preference for endpoints within non-linguistic motion events extends to relatively unfamiliar action lacking a concrete goal object, such as figure skating.

Endpoints often serve as pivotal moments that define parts and subparts within continuous events. Baking a soufflé, for example, is comprised of discrete steps (separate eggs, beat whites, fold batter) that demarcate critical junctures which influence whether or not the dessert will puff as planned. Attention to endpoints within dynamic events is theorized to be one of the first tools infants use to understand complex human behavior (Baldwin, Baird, Saylor, & Clark, 2001; Kim & Song, 2015; Leslie, 1993; Poulin-Dubois & Schultz, 1988; Premack, 1990; Wellman, 1992). In one study, Lakusta, Wagner, O'Hearn, and Landau (2007) presented 12-month-olds with a visual action in which an animate appearing agent (e.g., a toy duck) appeared to move from location A (e.g., a block) to location B (e.g., a bowl) repeatedly until the infants' initial interest waned. Infants resumed attention when changes occurred at the endpoint (e.g., bowl became a box), but failed to notice comparable changes at the starting point, controlling for which object was present at each location and the amount of time the duck spent at each location. Only after it was perceptually highlighted with "puffs, bows, and sequins," did the point of action initiation (i.e., starting point) garner infant attention (Lakusta et al., 2007). Subsequent studies revealed that visual preference for endpoints over starting points held for agentive but not non-agentive motion (e.g., floating balloon in Lakusta & Carey, 2015; leaf or tissue in Lakusta & DiFabrizio, 2017), suggesting that the endpoint bias may be restricted in infancy to intentional motion by an agent whose action culminates at a goal location. Whether the endpoint bias extends to animate action that is not bounded in space by a physical location (box, bowl) has yet to be determined.

Endpoints that mark the accomplishment of intentional actions (i.e., goals) appear to play an important role in early event representation, even for newborns (Craighero, Leo, Umiltà, & Simion, 2011). Even if the purpose is not apparent on the surface (e.g., dancing), human action is intrinsically goal-directed, or guided by the actor's intent to achieve some objective (e.g., for fun, for exercise, to perform, or to win a competition). When a 6-month-old views an adult repeatedly reach for an object (e.g., a teddy bear), the infant may not know the larger purpose or intent of the action (e.g., to play, to share, to hug, etc.), but she does recognize when the adult's movement is consistently directed toward a particular object, and looks longer during test trials if the adult grasps a different object (Daum, Prinz, & Aschersleben, 2008; Woodward, 1998). Importantly, infants 10–11 months of age notice when the attainment of a goal-directed action (e.g., reaching for an object) is interrupted by a still-frame pause inserted into the video, but show no increased attention when the pause aligns with action completion (Baldwin et al., 2001).

Not only do infants associate goal objects (e.g., teddy bear) with agentive action in their first year (Cannon & Woodward, 2012), but they also prioritize endpoints over other information in observed motion events, including the source (Lakusta & DiFabrizio, 2017), path (Buresh & Woodward, 2007; Woodward, 1998), and manner of motion (Carpenter, Call, & Tomasello, 2005) before age 2. Converging neurophysiological evidence shows sensitivity to endpoints of goal-directed action before the first birthday, particularly when these actions are familiar (e.g., eating; Reid et al., 2009) or when they coincide with an effect or outcome (e.g., flashing light; Monroy et al., 2019). Together these findings underscore infants' capacity to distinguish endpoints from other moments in an event and suggest that infants may segment human action using endpoints as an event parsing tool. Attention to endpoints in agentive action lacking an object-directed focus has received less attention and is of great import because human behavior is just as likely to flow freely from moment to moment without objects or outcomes to mark meaningful segments.

Although infants younger than one year do not typically have the language to describe motion events, a rich literature explores parallels between infants' early sensitivities to non-linguistic event components and the way these conceptual elements are eventually encoded in language (Maffongelli, D'Ausilio, Fadiga, & Daum, 2019; Mandler, 2004). The agent's trajectory in prototypical motion events such as those described in linguistic theory (Jackendoff, 1983; Talmy, 1985) and tested in Lakusta et al. (2007), can be separated into *source paths* in which the figure (duck) moves from a reference object that is the starting location (block), and *goal paths*, in which the figure moves to a reference object (bowl) that coincides with its ending location. Across languages, goal paths appear to be emphasized over source paths in the linguistic constructions adults (Regier & Zheng, 2007) and young children (Lakusta & Landau, 2012) produce when describing motion events. There is, of course, some question as to how closely the linguistic categories of source and goal are linked with nonlinguistic representations of starting points and endpoints. Not all endpoints qualify as goals (i.e., a vase will shatter if someone knocks it onto the floor, but this is rarely the intended outcome); similarly, sources are conceptually more abstract than starting points defined by physical, spatial, or temporal parameters and starting points may not always be sources (as in change events like a yellow chameleon turning green). In line with previous research, we use the terms 'starting point' and 'endpoint' when describing features of nonlinguistic motion event representations, but refer to the more abstract language categories of 'sources' and 'goals' when discussing how these concepts are encoded linguistically. In the General Discussion, we consider implications for theoretical questions of language acquisition and event representation stemming from this quandary.

It has been suggested that attention to endpoints over starting points may reflect differences in how these elements are represented syntactically and semantically (Papafragou, 2010; Regier & Zheng, 2007). For example, endpoints in English are often marked by a direct object in transitive linguistic frames (e.g., she ate [the apple]; he kissed [the baby]) or form *telic* predicates that are naturally bounded by a prepositional phrase (e.g., she skipped [to the tree]) in intransitive frames, whose predicates refer to actions lacking direct objects. Starting points, in contrast, are encoded by prepositional phrases that modify the process of the event (e.g., she skipped [from the tree]) or tend to be *atelic* in that the skipping action does not necessarily entail a specified conclusion without the addition of an optional adjunct. Despite early demonstration of a robust preference for endpoints over starting points, scant evidence exists as to whether infants differentially attend to endpoints when actions are not bounded by a goal object or a physical location. Indeed, a large-scale replication recently called into question whether infants' visual attention to endpoints in goal-directed action paradigms have more to do with anticipation of the agent's path than goal (Ganglmayer, Attig, Daum, & Paulus, 2019)

In the present study, our interest lies primarily with investigating infants' attention to endpoints as compared to starting points for an underexplored type of motion event in which the agent's action is relatively unfamiliar, is not defined by a goal object, and has no explicit culmination or outcome (i.e., lacks a goal location signified by a physical object). Linguistically, this type of action could be expressed as having an intransitive predicate with atelic aspect, and it is currently unknown whether attention to endpoints generalizes more broadly to this type of action in which the "goal" accomplishment is measured not by an object or spatial location, but rather by the ending state of the action itself. This investigation builds upon the field's current understanding of infants' preference in nonlinguistic events for endpoints when they coincide with the attainment of a prominent goal object or arrival at a goal location (Adam et al., 2016; Cannon & Woodward, 2012; Kanakogi & Itakura, 2011; Krogh-Jespersen & Woodward, 2014), and those events in which the endpoint is marked by a salient outcome, like a co-occurring sound or flash of light (Buchsbaum, Gopnik, Griffiths, & Shafto, 2011; Monroy et al., 2019). It also extends related research showing that infants as young as 4 months of age appear to integrate information about body form and motion during action observation performed by biological (i.e., human) and non-biological (i.e., Lego) agents (Grossmann, Cross, Ticini, & Daum, 2013).

Prior research with adults indicates that attention to endpoints may enable the segmentation of atelic actions that are both intransitive and relatively unfamiliar (Levine, Hirsh-Pasek, Pace, & Golinkoff, 2017) and colleagues asked four different groups of adults to segment a video of Olympic figure skating, by pressing a button any time they detected a boundary in the event. The groups were as follows: experts (i.e., Olympic figure skating trainers), novices, novices familiarized with the video prior to parsing, and novices viewing the video in reverse. Starting and ending points (i.e., defined by a separate group of ice skating coaches) were consistently marked as boundaries in the event by all groups, but with a strong bias toward endpoints. Even novices viewing the backwards event, wherein endpoints became starting points and starting points became endpoints, marked significantly more boundaries at the action completion (previously the starting point in the forwards event) equivalent to the other novice groups. This result suggests that attention to endpoints is not attributable to a particular constellation of perceptual cues, but rather may be a result of the attribution of goal achievement to the agent in motion. Using functional imaging, some research has also documented that the adult brain may distinguish between telic verbs that refer to events with a naturally specified endpoint (e.g., reaching), and atelic verbs with no delimitation (e.g., chasing) even when these verbs are controlled for other semantic features such as dynamicity, animacy, and imageability (Romagno, Rota, Ricciardi, & Pietrini, 2012). However, unlike infants, adults – even novices to ice skating – have relevant prior experiences, language, and biases that may facilitate their ability to reliably segment actions using information available at endpoints (Zacks, Tversky, & Iyer, 2001).

Neurophysiological studies of infants' action observation provide some initial evidence that parsing actions lacking goal objects may in fact be challenging. One study found that infants between 8–11 months were able to detect violations to learned regularities within actions sequences (i.e., during a training phase) that included deterministic pairs (i.e., 100 % transitional probability) embedded within an otherwise random sequence (Monroy et al., 2019). For this study, infants observed a video of an adult's hands performing a sequence of actions (e.g., bend, open, slide) on a novel toy that included six unique objects (e.g., blue square button, round red joystick, yellow rectangular door) and a central star-shaped light. Half of the deterministic action pairs resulted in an action-effect (light on) whereas the other half had no effect. Anticipatory eye-gaze patterns indicated that the infants had learned which actions were paired together, but this effect was modulated by whether or not the upcoming action was associated with the salient outcome (i.e., star light). Infants' event-related potentials (ERPs; i.e., voltage oscillations in the electroencephalography signal recorded at the scalp that are time-locked to the onset of a perceived stimulus; Luck, 2014) mirrored this behavioral finding, revealing greater negative amplitude waveforms at broad electrode sites between 250 and 750 ms in response to violations of the outcome to the learned action-effect pairs, but not to non-effect pairs. This ERP pattern is consistent with the Nc component (Reynolds, 2015) and may index infants' ability to rapidly learn about the structure of observed object-directed action sequences using statistical regularities, but only for events which include a salient effect.

Additional ERP research has focused on highly familiar actions (e.g., eating) with salient goal-directed outcomes (e.g., food to mouth) involving a central object (e.g., spoon) (e.g., Reid et al., 2009). From this research, it appears that very young infants (i.e., as young as 5 months; Michel, Kaduk, Ní Choisdealbha, & Reid, 2017) display N400-like electrophysiological responses (i.e., a mid-latency negativity peaking at central-parietal electrodes) to action outcomes that violate semantic expectations, such as bringing a spoonful of food to one's forehead (Kaduk et al., 2016; Reid et al., 2009). Older children (~ 24 months) demonstrate a similar pattern of N400-like electrophysiological response to the disruption of expected outcomes to relatively novel events after a brief familiarization phase (Pace, Carver, & Friend, 2013).

Other recent ERP research has also focused on infants' ability to detect statistical regularities in goal-directed action sequences, revealing that attentional engagement may be influenced by expectations about action outcomes or endpoints. In a between-subjects design, for instance, 14-month-old infants were familiarized with either full demonstrations, failed attempts, or arbitrary versions of goal-directed actions involving a goal object (e.g., pulling apart a dumbbell, closing a box; Schönebeck & Elsner, 2019). Infants in both the failed-attempt and full-demonstration conditions had larger negative electrophysiological responses to still images that depicted complete compared to incomplete end-states of object-directed action during exogenous epochs (100 – 200 ms), but there were no differences for end-states that infants had already seen during familiarization. Slow-wave activity (700 – 1000 ms) differed for end-state pictures across conditions, suggesting differential memory encoding demands based on which actions the infants had observed during familiarization. It remains an open inquiry whether infants also attend to endpoints within motion events characterized by unfamiliar intransitive human action, particularly when the actions are atelic in nature having no natural point of completion.

To address this question regarding infants' attention to endpoints within motion events more broadly construed, the current research used eye-tracking and neurophysiological methods to examine infants' responses to an unfamiliar and complex but naturalistic human action event: figure skating. In a two-minute routine, figure skaters perform a series of fluid and complex actions, like the triple toe lutz, each bounded by a starting point and endpoint in space and time. Infants have no *a priori* knowledge of the "goals" of figure skating actions; the endpoints are defined by novel movement patterns, just as are the paths, manners, and starting points of figure skating actions. This contrasts widely with the salient, concrete goals of the highly familiar and simplistic actions used in prior studies (e.g., Baldwin et al., 2001; Lakusta et al., 2007; Reid et al., 2009). Measures of visual attention and event-related potentials were utilized here to reveal whether infants displayed sensitivity to endpoints within unfamiliar, intransitive figure skating actions. We include infants near their first birthdays because this period corresponds with emerging ability to process human action and action intentions, but precedes the acquisition of vocabulary that may influence event representations. In both the behavioral and ERP paradigms, disruptions to the continuous flow of action were inserted at the starting point, ending point, or within-action locations. Infant responses to disruptions were compared across conditions. We hypothesized that pauses occurring at action endings would elicit behavioral and electrophysiological responses that were distinguishable from pauses occurring at other meaningful locations within the action (i.e., starting points) or at arbitrary locations in the action (i.e., within-action).

Such an extension may be relevant because for much of human behavior the goal of the action may simply be the completion of a particular movement (Schachner & Carey, 2013). This is true for actions as commonplace and repetitive as walking and as unfamiliar and dynamic as figure skating—the moment of completion is not marked by a tangible object but marked by a pattern of motion. A broad extension would also be relevant because it may provide a toehold for infants to find meaningful units of action that map onto language. Here we ask whether infant sensitivity to endpoints that has been demonstrated for animate, object-directed motion (e.g., Lakusta et al., 2007) extends to animate motion in which there is no stoppage in the action and the scene does not contain a concrete goal object. We test this using both eye-tracking methods as well as event-related potentials to investigate behavioral and electrophysiological responses to disruptions within intransitive actions (i.e., Olympic figure skating).

2. Study 1: do infants show visual preference for endpoints in unfamiliar, intransitive action events?

Study 1 used eye-tracking to explore infants' sensitivity to endpoints within a dynamic series of intransitive figure skating actions. We tested the hypothesis that infants detect endpoints as boundaries, by comparing infants' visual attention when artificial pauses (i.e., inserted into videotaped segments) align with action completion (i.e., endpoints) and when pauses occur at action initiation (i.e., starting points) or within-action locations. Given prior research revealing infants' visual sensitivity to endpoints within continuous motion that is both familiar and transitive (Kline, Snedeker, & Schulz, 2017; Lakusta et al., 2007) and evidence of adults' ability to parse unfamiliar, intransitive actions at goals (author references), we predicted that infants would demonstrate visual preferences for unfamiliar, intransitive actions containing pauses at endpoints over pauses at other locations. Artificial pauses were expected to draw more visual attention when they aligned with endpoints than when they occurred at arbitrary within-action locations or at starting points, since goal completion in agentive action is highly salient in early infancy.

2.1. Method

2.1.1. Participants

Forty-eight healthy full-term infants (30 girls), aged 10–14 months (*mean age* = 11.95 months, *SD* = 1.46; *range* = 10.03–14.73 months) from monolingual, English-speaking homes were included in analyses. Nineteen additional infants were excluded because of failure to calibrate (3), fussiness (8), equipment malfunction (7), and prematurity (1). Infants were recruited from a suburb of Philadelphia that is predominantly middle to upper-middle class. Procedures were approved by the Institutional Review Board and written consent was obtained from caregivers.

Infants were randomly entered into one of three conditions in a between-subjects design, for a total of sixteen infants per condition. One group viewed figure skating segments with pauses inserted at starting points, a second group viewed the segments with pauses at endpoints, and a third group viewed the segments with pauses inserted within action boundaries. Preliminary analyses revealed no differences between the three conditions in terms of age or gender (ps > .4).

2.1.2. Materials and procedure

Visual stimuli were dynamic actions selected from a 172-second silent clip of Michelle Kwan, an international figure-skating champion, performing her short program routine at the 1998 Olympics. Eight figure-skating actions within this video were carefully defined and agreed-upon with high reliability by Olympic trainer expert consultants in a prior study (blinded for review). Five of these actions were selected for the current study, and the remaining three were excluded because their length exceeded 10 s. The selected actions were extracted from the video, along with three seconds of continuous skating before and after each action resulting in five video segments. Continuous motion before the action initiation and after the action completion was critical in that it argues against the possibility that infant attention was simply directed toward the beginnings and endings of physical movement, rather than meaningful components of an action that may serve as conceptual sources and goals within a motion event (Wagner & Lakusta, 2009).

Still-frame pauses of a 1.5-second duration were artificially inserted within the continuous segments at one of three previously

Table 1
Duration of Figure Skating Action Segments and Timing of Still-Frame Pauses.

Figure Skating Action	Total Segment Duration (seconds)	Pause Location (seconds into segment)		
		Starting Point	Within-Action	Endpoint
Triple Lutz double toe	12.38	3.00	6.79	7.84
Double axel	9.17	3.00	3.60	4.67
Layback spin	16.88	3.00	9.80	12.37
Triple flip	10.61	3.00	4.74	6.11
Flying sit spin (death drop)	16.39	3.00	4.09	11.89

Note. Each pause lasted 1.5-s and is included in the total segment duration. All pauses at starting points began exactly 3 s into the segment, and all pauses at endpoints ended exactly 3 s prior to the end of the segment. Figure skating actions are listed in the order in which these segments appeared in the video.

determined locations: starting point, endpoint, or within-action. This method borrows from the speech perception literature and the literature on event segmentation, in which a pause is placed either at a clausal/event boundary or at a non-boundary location (Baldwin et al., 2001; Hirsh-Pasek et al., 1987). For the within-action pauses, care was taken to avoid violating the physical laws of biological motion. These pauses were therefore not midpoints of actions, to avoid pauses occurring while the skater was mid-air or spinning at high speeds. Table 1 shows the total duration of each of the five figure skating action segments as well as the timing of the still-frame pauses at each action's starting point, endpoint, and within-action location.

Infants were seated on their parent's lap facing a 30-inch monitor (refresh rate = 60 Hz, resolution = 720 × 480 pixels, 16-bit color mode) and table-mounted eye-tracking device (Tobii X60, Stockholm, Sweden). The viewing distance was approximately 60 cm from the monitor. Prior to beginning the experiment, the eye-tracker was calibrated using a 5-point display to accurately track infants' eyes. Individual calibration points highlighted as unreliable by the program were repeated until reliability was obtained. The eye-tracker recorded infants' binocular eye fixations at a sampling rate of 60 Hz. To prevent parental influence on infants' looking behavior, parents wore occluding sunglasses or closed their eyes for the duration of the study.

Infants in each condition viewed the five figure skating segments, looped three times, with pauses inserted at the designated location according to condition assignment (starting point, ending point, or within-action). A 3-second clip of a laughing baby was used as an attention-getter, to recapture infants' attention immediately prior to each segment. In all conditions, infants viewed the same segments in the same order. Infants' visual attention to the figure skating segments, measured as the proportion of looking time to each of the five figure skating segments with the area of interest defined as the full-screen video, was compared across conditions.

2.2. Results

First, to provide a baseline measure of looking time for the three groups, we examined infants' proportion of looking to the attention getter. A one-way analysis of variance (ANOVA) revealed no significant differences between the three groups on their visual attention to the attention getter, $F(2,47) = .16, p = .86$ (group with pauses at starting points: $M = .75$, $SE = .054$; group with pauses within-action: $M = .78$, $SE = .056$; group with pauses at endpoints: $M = .79$, $SE = .059$). However, due to the potential effect of small individual differences in baseline attention on performance in the main task, we included infants' baseline attention as a covariate in subsequent analyses.

The proportion of infants' looking time was calculated for each of the 5 figure skating actions by dividing the number of seconds spent looking at the screen during each trial by the total number of seconds in the trial and averaging across the three trials for each action segment. We conducted a mixed model analysis of covariance (ANCOVA) to test the hypothesis that infants would show a visual preference for pauses that aligned with action endpoints, controlling for group differences in baseline attention. Condition (pauses at action starting points, pauses within-action, and pauses at action endpoints) was entered as the between-subjects factor, and Segment (triple lutz double toe, double axel, layback spin, triple flip, and flying sit spin) was entered as the within-subjects factor, with Baseline Attention included as a covariate. The analysis revealed a significant main effect of Condition, $F(2,44) = 3.80$, $p = .030$, $\eta^2_{partial} = .15$ (Fig. 1). Pairwise comparisons using Tukey's honestly significant difference (HSD) indicated that infants viewing action segments with pauses inserted at endpoints looked longer to the segments ($M = .59$, $SE = .034$) than infants viewing action segments with pauses at starting points ($M = .49$, $SE = .034$, $p = .047$) or infants viewing action segments with within-action pauses ($M = .46$, $SE = .034$, $p = .012$; Fig. 1), but there was no significant difference in looking time between infants viewing pauses at starting points and pauses within actions ($p = .57$). There was no significant main effect of Segment, $F(4, 176) = .99$, $p = .42$, and the interactions between Segment and Condition and between Segment and Baseline Attention were not significant ($ps > .5$).

The analysis described above compared across conditions infants' looking to all 15 trials, with no minimum requirements of looking during each trial, because of the *a priori* hypothesis that pauses consistently placed at a particular location in the action would have a cumulative effect on infants' visual attention to the action segments. However, an alternative approach would be to include in the analyses only trials in which infants viewed the pause. Therefore, we reran the mixed model ANCOVA excluding trials in which infants did not view any of the pause (i.e., fixation duration of 0 s for the pause). This led to the loss of an average of 1.50 trials per infant ($SE = .23$) out of the 15 total trials; infants' looking times across non-excluded trials were then averaged for each of the five action segments.

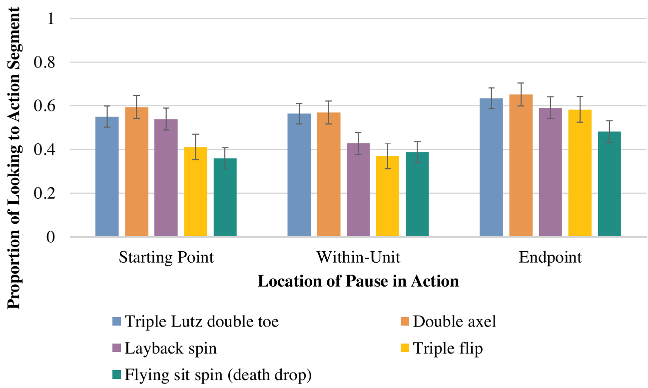

Fig. 1. Mixed model analysis of covariance: effects of pause location and action segment on proportion of 10- to 14-month-old infants' looking to action segments.

The main effect of Condition on infants' attention to the action segments was trending toward significance, $F(2,44) = 2.94$, $p = .064$, $\eta^2_{partial} = .12$, with a pattern of results similar to the previous analysis. Pairwise comparisons using Tukey's HSD indicated that there was a significant difference between infants viewing endpoint pauses ($M = .59$, $SE = .035$) and infants viewing within-action pauses ($M = .48$, $SE = .035$, $p = .025$), a trending difference between infants viewing endpoint pauses and those viewing starting point pauses ($M = .51$, $SE = .035$, $p = .084$), and no difference between infants viewing starting point pauses and within-action pauses ($p = .66$). There was again no significant main effect of Segment and no significant interactions ($ps > .3$).

2.3. Discussion

Study 1 asked whether infants would show sensitivity to the endpoints of unfamiliar, intransitive actions such as figure skating. We predicted that if infants extract these endpoints as event boundaries similar to adults (blinded for review), then artificial pauses aligning with endpoints should attract infant attention relative to pauses inserted elsewhere in the action. Indeed, when pauses aligned with figure skating endpoints, infants' visual attention for the action was greater than when pauses aligned with starting points or when pauses occurred within actions. Infants were sensitive to these movement boundaries within continuous motion, suggesting that infants may parse novel, intransitive action events guided by attention to the endpoints of actions.

This finding expands the growing body of work examining infants' action segmentation, revealing that infants' attention to endpoints in continuous action is not limited to object-directed motion, but rather applies also to dynamic human motion lacking tangible goal objects. The capacity to segment intransitive actions at endpoints seems to be available to infants by approximately the same time they segment transitive actions (Baldwin et al., 2001). Thus, infants' sensitivity to endpoints may not require a clear goal-object to signal attainment (e.g., spoon in mouth) but may rely more broadly on the confluence of cues available during goal achievement or action completion even in the context of unfamiliar dynamic human action.

It is important to note that the pattern of looking identified in this study was different from the pattern described by Baldwin et al. (2001). In Baldwin's seminal work, infant attention was greater to the mid-action interruption whereas attention allocation appeared to be greater to the endpoint interruption in the present study. There are two plausible explanations for this distinction. The first has to do with the level of action familiarity. Baldwin and colleagues utilized videos of continuous everyday action (e.g., a woman bending down to pick up a towel or pick up ice cream). Importantly, infants only had a preference for interrupting test videos when they were first habituated to the event structure *without* any pauses. Second, Baldwin's study included a clearly identified goal object (i.e., towel or ice cream) that served to demarcate the completion of the action. Thus, it is likely that infants constructed an action template based on the familiarization phase which served to highlight the disruption in the interrupting test video with respect to the anticipated goal attainment (e.g., grasping an object). In the present study, we used unfamiliar actions and did not include a habituation phase, nor did a goal object serve as a visually salient cue to the action boundary. Without these markers, it appears that pauses aligning with action endpoints became more salient than pauses coinciding with arbitrary moments of action or pauses marking the onset of the action.

Alternatively, it is possible that infants' increased interest to pauses occurring at endpoints was not an enhanced sensitivity to the goal, but in fact an *avoidance* of pauses at locations that are perceived as unnatural (i.e., at starting points or within-action locations). Within a large parallel literature in the language domain (Saffran, Senghas, & Trueswell, 2001), this interpretation would be consistent with a preference shown by 11-month-olds to listen significantly longer to fluent speech that was disrupted with 1-second pauses at natural boundaries occurring between successive words (i.e., coincident versions), rather than between syllables within words (i.e., noncoincident versions; Myers et al., 1996) and 7- to 10-month-olds who showed a similar preference for pauses occurring at clause boundaries rather than within-clause boundaries (Hirsk-Pasek et al., 1987). Moreover, infants in the current study ranged in age from 10 to 14 months. This period of development covers the important motor milestone of taking the first independent steps, which may change how infants perceive actions that involve independent bipedal locomotion (Sanefuji, Ohgami, & Hashiya, 2008). Future research should investigate whether results vary as a function of motor skill development.

A limitation of this study is that pauses at endpoints necessarily occur later in time than pauses at starting points, so it is difficult to rule out the possibility that differences in looking time across conditions could have been due to differences in the length of uninterrupted action viewed prior to the pause. However, a supplementary analysis examining this alternative hypothesis more closely does not support this conclusion.[1]

Behavioral evidence alone cannot conclusively discern whether looking preferences were due to increased interest at goal locations or avoidance of disruptions at other locations. Including a neurophysiological dimension provides the opportunity to interpret converging or conflicting response patterns and enables investigation into the time-course of action processing. In addition to interpreting infants' understanding of endpoints by measuring their looking behavior, it is also of interest to determine how the infant brain responds to event structure. Neurophysiological measures might show identical patterns to behavior or may be even more sensitive than behavioral measures. In Study 2, we used event-related potentials (ERP) to assess brain responses to the same stimuli viewed by infants in Study 1.

3. Study 2: what are the electrophysiological correlates of endpoint detection in unfamiliar, intransitive action events?

One benefit of the ERP methodology is high temporal resolution, measuring electrophysiological responses to the presentation of a stimulus with millisecond accuracy. Thus, the ERP methodology might be particularly suited to the study of event representation, as actions may be processed on multiple levels as they unfold over time. Of interest in this study are the neural mechanisms that support infants' detection of endpoints in unfamiliar, intransitive action events. The current paradigm recorded continuous electroencephalogram (EEG) as infants observed figure skating segments in which artificial pauses were aligned with starting points, endpoints, or within-action locations (identical to Study 1). Following prior work with infants on event representation, mean amplitudes were analyzed within three windows of interest (early, mid, and late) intending to capture components associated with perceptual, semantic, and memory updating processes in response to dynamic action (Pace et al., 2013; Schönebeck & Elsner, 2019).

Early components occurring prior to 200 ms after stimulus onset are thought to reflect processing of perceptual stimulus features such as size, shape, or luminance (Hillyard & Anllo-Vento, 1998; Hillyard, Teder-Sälejärvi, & Münte, 1998; Thierry, 2005) and have been identified in response to stimuli depicting relatively novel goal-directed action (Pace et al., 2013; Schönebeck & Elsner, 2019). In the current study, we tested for differences emerging between 0 and 200 ms and predicted that pauses aligning with endpoints would elicit ERPs with larger negative amplitudes relative to pauses in other action locations.

Mid-latency components are thought to reflect conceptual processes such as semantic analysis or attention and have been identified in response to event processing in children and adults (Bach, Gunter, Knoblich, Prinz, & Friederici, 2009; Hamm, Johnson, & Kirk, 2002; Sitnikova, Kuperberg, & Holcomb, 2003; Sitnikova, Holcomb, Kiyonaga, & Kuperberg, 2008; West & Holcomb, 2002). Of particular interest is the Negative central, or Nc component, characterized by increased negative amplitude at central and midline electrodes, peaking between 250 and 750 ms following stimulus onset (Reynolds, 2015). Another mid-latency ERP component frequently investigated in the context of action processing is the N400. The N400-effect is a negative going waveform that peaks around ~400 ms in adults and has been linked with semantic mismatch within adult and child populations when a perceived action violates expectations relative to the observed context (Amoruso et al., 2013 provides a review of the N400 in event contexts). In the context of goal-directed actions, N400-like responses can be interpreted as evidence that infants and young children are actively working to integrate action outcomes or conclusions into their overarching event representations. As there is no logical, object-focused conclusion to the completion of a figure skating movement, the current research did not expect an N400-like effect as a result of the disruptions to any condition.

Slow-wave activity occurring post 700 ms at broadly distributed scalp locations has been taken to reflect infants' memory encoding of visual stimuli (Nelson & Collins, 1991; Webb, Long, & Nelson, 2005). Although slow-wave activity has not been extensively investigated in the context of action processing in infancy, there is evidence for positive slow wave (PSW) as an index of memory updating or encoding processes (Schönebeck & Elsner, 2019), and the negative slow wave (NSW) as an index of novelty detection (de Haan, 2007; Reynolds & Richards, 2005) within event paradigms. Recent research has focused on infants' ability to detect statistical regularities in goal-directed action sequences, revealing that attentional engagement may be influenced by relative salience and expectations about action outcomes or endpoints.

We reasoned that if infants were sensitive to event structure within unfamiliar intransitive action (i.e., without salient goal-objects to mark action completion), pauses inserted at various locations within figure skating action segments (starting points, endpoints, or within-action locations) should produce ERP responses that differentiate between conditions. We analyzed early-latency waveforms occurring between 0 and 200 ms; mid-latency waveforms between 250 − 750 ms; and long-latency waveforms occurring between 700 − 1000 ms. In early-latency epochs we expected to find greater negativities in response to pauses at endpoints compared to other

[1] A mixed model ANCOVA was run excluding the first segment, to ensure that the analyzed data did not include uninterrupted event viewing before children in all conditions had seen still-frame pauses in the video. Additionally, by beginning analyses at the second segment, the most recently viewed pause occurred in the endpoints condition, making it more likely that children in this condition would watch the video less than those in other conditions, if the alternative hypothesis that any pause was equally disruptive was true. In fact, findings were similar to when the first segment was included, with a main effect of Condition, $F(2,44) = 3.84$, $p = .029$, $\eta^2_{partial} = .15$, Pairwise comparisons indicated a significant difference between infants viewing endpoint pauses ($M = .58$, $SE = .036$) and infants viewing within-action pauses ($M = .44$, $SE = .036$, $p = .009$), a trending difference between infants viewing endpoint pauses and those viewing starting point pauses ($M = .49$, $SE = .036$, $p = .081$), and no difference between infants viewing starting point pauses and within-action pauses ($p = .36$).

pause locations (starting points, within-action) based on prior ERP evidence for attention to salient action effects in a group of 14-month-old infants (Schönebeck & Elsner, 2019) and behavioral evidence that infants are highly sensitive to biological motion (Simion, Regolin, & Bulf, 2008).

Within mid-latency windows, we expected to find an Nc component in prefrontal and frontal regions between 250 and 750 ms in response to pauses at endpoints based on evidence that endpoints may recruit greater allocation of attentional resources, level of engagement, or general orienting in infancy. Slow wave activity after 700 ms may index extended reconciliation of actions within overall event structure, and we again expected increased activity in response to pauses at endpoints within this window. Because the paradigm was relatively novel and we did not have prior evidence from similar motion events to guide our predictions, we did not have specific hypotheses about the polarity of ERP effects (negative, positive) in the later epoch.

3.1. Method

3.1.1. Participants

Twenty-one infants participated (13 girls), aged 10–11 months (*mean age* = 11.1 months; *range* = 10.0–11.5 months). All infants were from monolingual, English-speaking homes. Because the goal of the study was to examine typical brain development, only infants who experienced a normal, uncomplicated birth and a normal course of development were included. Additional infants were tested but were excluded due to experimenter error ($N = 1$) or because they did not contribute enough trials as a result of excessive noise or motion artifact ($N = 29$). All infants were recruited from a city in Southern California and were born full-term (37–41 weeks). Procedures were approved by the Institutional Review Board and written consent was obtained from caregivers. Because of the length of test session that would be required to conduct a completely within-subjects comparison, infants were randomly assigned to view figure skating segments with pauses inserted at two out of three locations: Starting Point and Within-Action; Starting Point and Endpoint locations; or Within-Action and Endpoint locations.

3.1.2. Materials

Figure skating segments (identical to those described in Study 1) were digitized using iMovie into still frames (at 20 fps). For each of the five figure skating segments, the authors selected still images that captured the defining structure of the action and included 8–12 frames of continuous figure skating before and after each segment. Presentation of still frames in lieu of video has been used to study gesture (Sheehan, Namy, & Mills, 2007; Stürmer, Aschersleben, & Prinz, 2000), sign language (Neville et al., 1997), action perception (Kourtzi & Kanwisher, 2000), event segmentation (Pace et al., 2013; Reid et al., 2009), and the effect of visually depicted actions (e.g., punching, applauding) on language comprehension (Knoeferle, Urbach, & Kutas, 2011). Static frames were chosen because they provide a clear onset for time-locking the ERP stimuli and research indicates that they are processed in ways similar to dynamic events (Bach et al., 2009).

Frames remained on screen for 150 ms each and were presented in rapid succession (< 10 ms ISI) to preserve temporal dependencies within each segment. Due to the variable length of each skating segment, the number of frames varied from 60 to 91 frames ($M = 67$ frames; $SD = 18.47$ frames). Pauses were created by presenting 10 identical still frames of 150 ms each to create a 1500 ms pause, identical to the pause duration in Study 1. ERPs were time-locked to the onset of the pause in each condition. As in Study 1, within-action pauses were not midpoints of actions, but were instead selected as arbitrary moments that did not coincide with a starting point or ending point. Due to the nature of the skating actions, the positioning of pauses was variable across conditions. Table 2 shows target frames for each condition by action segment.

3.1.3. ERP design and procedure

Infants wore a standard, fitted cap (Electrocap International, Eaton, OH) with electrodes placed according to the international 10–20 system. Continuous EEG was recorded with a NeuroScan 4.5 System (Compumedics, Charlotte, NC, USA) with a reference electrode at Cz and re-referenced offline to the average activity at left and right mastoids. ERPs were recorded at 33 scalp locations using silver/silver-chloride (Ag/AgCl) electrodes at standard sites (Pz, Fz, O1, O2, P3, P4, T3, T4, T5, T6, C3, C4, Cz, F3, F4, F7, F8, A1, A2) and additional sites (CPz, FCz, CP5, CP6, CP1, CP2, FC1, FC2, FC5, FC6, FP1, FP2, AF7, AF8). Electrode resistance was kept under 10kOhms. Continuous EEG was amplified with a low-pass filter (70 Hz), a directly coupled high-pass filter (DC), and a notch filter (60 Hz). The signal was digitized at a rate of 500 samples per second via an Analog-to-Digital converter. A Logitech webcam was used to determine whether infants were paying attention to the pauses within each video segment. When infants lost eye contact with stimuli, it was manually marked with Scan4.5 program on ERP data acquisition computer and these trials were excluded from analyses. Eye movement artifacts and blinks were monitored via horizontal electrooculogram (EOG) placed at the outer canthi of

Table 2
Pause locations by condition and action in ERP stimuli.

	Starting Point	Within-Action	Endpoint	Total Frames
Action 1	Frame 12	Frame 34	Frame 43	60
Action 2	Frame16	Frame 18	Frame 31	47
Action 3	Frame 14	Frame 50	Frame 65	81
Action 4	Frame 17	Frame 25	Frame 37	55
Action 5	Frame 17	Frame 24	Frame 74	91

each eye and vertical EOG placed above and below the left eye. ERP trials were time-locked to the onset of the still frame in each condition.

After the experiment, EEG signals were analyzed using EEGLAB (version 9_0_8_6b; http://sccn.ucsd.edu/eeglab; Delorme & Makeig, 2004), in the MATLAB environment (The Mathwords, Natick, MA, USA). First, data were visually inspected and trials in which the amplitude of the activity deviated more than 200 μV from the baseline were excluded from further analyses. To remove additional artifacts, we used a moving window peak-to-peak procedure in ERPLab (Lopez-Calderon & Luck, 2014) with a 200 ms moving window, a 100 ms window step, and a 150 μV voltage threshold. Epochs of 1000 ms were computed with a pre-stimulus baseline of 100 ms, and baseline correction was performed (pre-stimulus interval). For their data to be retained for analysis, infants were required to have at least 5 artifact-free trials in each condition. Although this is a relatively small number of trials compared to other infant ERP studies, trial inclusion criterion was selected based on previous evidence suggesting reliable effects have been found in infancy with as few as three to seven trials per condition (Kaduk, Elsner, & Reid, 2013; Missana, Rajhans, Atkinson, & Grossmann, 2014; Monroy et al., 2019; Stets & Reid, 2011). Criteria for inclusion and exclusion continues to be an important issue for discussion, particularly as neurophysiological methods in infancy become more widely used.

We made strategic decisions regarding stimuli presentation based on pilot data collection and demonstrated limits to infant attention. Our paradigm required that infants attend to at least 5 full artifact-free trials for each condition, by observing the frames leading up to and including the critical pause in each trial. Therefore, infants were randomly assigned to view stimuli from two out of the three possible conditions in a partial within-subjects design. Figure skating segments were pseudo-randomized into a single block of 40 trials (20 per condition), lasting for approximately 11 min. An image of a smiling baby served as an attention-getter to re-orient the infant to the screen between trials. Final analyses included 7 infants who viewed a block comprised of Starting Point and Endpoint trials; 7 infants who viewed a block comprised of Starting Point and Within-Action trials; and 7 infants who viewed a block comprised of Within-Action and Endpoint trials. Infants provided an average of 7.86 artifact-free trials in the Starting Point condition (SD = 2.38; range = 5–12), 7.79 artifact-free trials in the Endpoint condition (SD = 3.53; range = 5–12), and 7.57 artifact-free trials in the Within-Action condition (SD = 2.47; range = 5–12). There was no significant difference in the number of trials analyzed between conditions or groups.

3.1.4. Analysis of ERP data

The ERP data were averaged separately for each condition (Starting Point, Endpoint, Within-Action) across subjects at electrodes of interest, creating grand-averaged waveforms. Data were analyzed using JMP (version 14.0) with the full-factorial repeated measures add-in for key epochs of interest. We analyzed data in three windows: an early-latency window (0 − 200 ms) associated with perceptual processing; a mid-latency window (250 − 750 ms) associated with attentional and conceptual processing; and a long latency window (700 − 1000 ms) associated with slow-wave activity indexing memory encoding. For each epoch we calculated mean amplitudes, following existing ERP work on action processing in infants as well as growing evidence for the superiority to peak amplitudes (Luck, 2018).

In the early-latency window (0 − 200 ms), we analyzed effects at fronto-central electrode sites in three predetermined regions: Left Hemisphere (LH: FP1, F3, FC1, FC5), Right Hemisphere (RH: FP2, F4, FC6, FC2), and Midline (Fz, FCz, Cz, CPz). Using JMPs Table Summary function, mean amplitudes were averaged across all four electrode sites to generate a single datapoint for each region by condition. In the mid-latency window (250–750), we analyzed effects in the LH, RH, and at the midline across four broad scalp regions: Frontal (F3, Fz, F4), Fronto-Central (FC1, FCz, FC2), Central (C3, Cz, C4) and Centro-Parietal (CP1, CPz, CP2), retaining Region and Laterality as factors in our analyses. For our long-latency window (700–1000), we analyzed effects in the LH (C3, CP1, CP5, P3); Midline (Cz, CPz, Pz), and RH (C4, CP2, CP6, P4), creating a single average across electrode sites in each group.

3.2. Results

Fig. 2 shows grand average waveforms across relevant electrodes in our three epochs of interest. In our early window, a repeated measures ANOVA of mean amplitudes showed a significant main effect of Condition $F(1, 16.44) = 5.21$, $p = .0360$. There was no significant effect of Region and no Condition X Region interaction ($ps > .05$). Ordered differences analyses indicated that this effect was driven by significant differences between the Endpoint (M = .542 μV; SE = 1.0) and Within-Action Conditions (M = −3.763 μV; SE = .875); Difference = 4.305 μV, SE = 1.42 μV, CI [1.49 μV; 7.92 μV]. No significant differences were found between the Starting Point condition (M = −1.705 μV; SE = 1.13) and either Within-Action or Endpoint conditions ($ps > .05$). Topographic plots (Fig. 3) display mean amplitudes across the scalp between 0 and 200 ms in each Condition; amplitudes in response to the Within-Action condition were significantly more negative than responses to the Endpoint condition.

For the mid-latency window (250–750), a full-factorial repeated measures ANOVA including Condition (Starting Point, Endpoint, Mid-action) X Region (Frontal, Fronto-central, Central, Centro-parietal) X Laterality (LH, Midline, RH), with Subject as a random factor, was conducted. The ANOVA revealed non-significant findings for Condition and Laterality, the Condition X Laterality interaction, and all other interactions. However, there was a significant main effect of Region, $F(3, 54.69) = 6.63$, $p = .0007$, with larger amplitudes at frontal scalp locations across all conditions as compared to posterior [*Means*: Frontal = 4.29 μV; Fronto-central = 3.96 μV; Central = 3.51 μV; Centro-parietal = 3.31 μV; SE: .51].

In our long-latency window (700–1000), mean amplitudes followed a similar pattern to earlier windows: Starting Point (M = −.69 μV; SE = .51), Mid-Action (M = −.75 μV; SE = .51), Endpoint (M = .31 μV; SE = .51). Yet, repeated measures ANOVAs again revealed non-significant effects for Condition, Region, and all interactions. However, Restricted Maximum Likelihood (REML) Variance Reports revealed high variability between infants in this epoch resulting in a significant Subject X Condition interaction

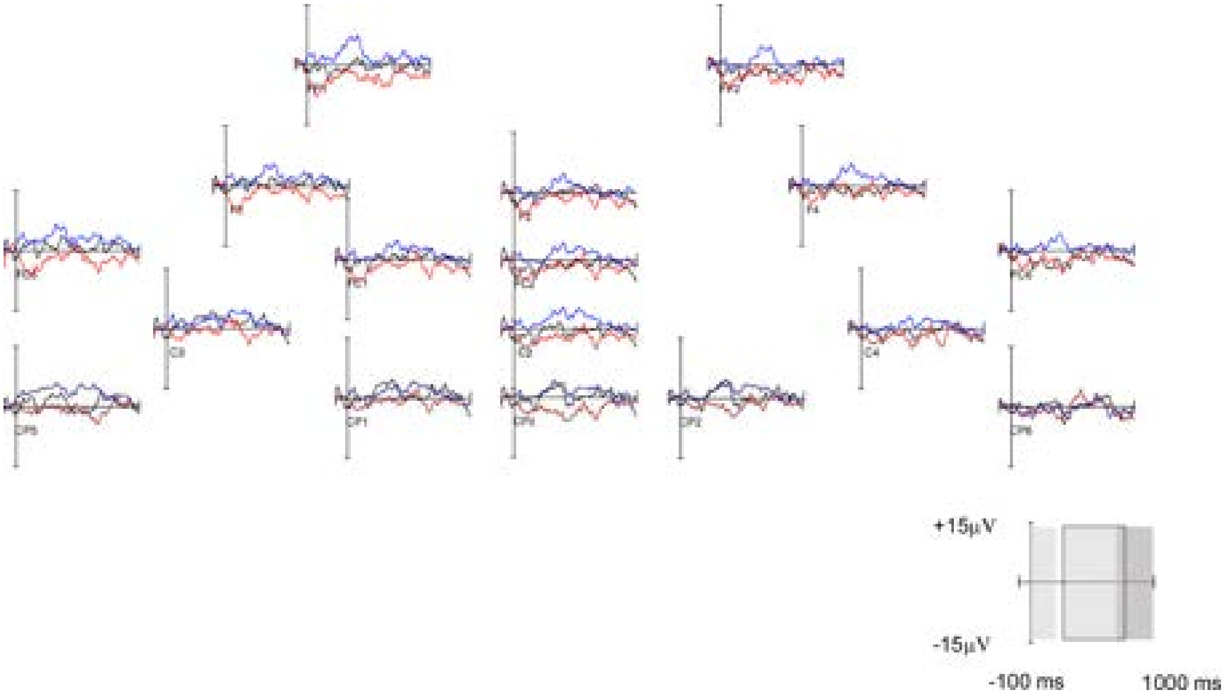

Fig. 2. Grand average waveforms for 10 to 11-month-old infants across all conditions at electrodes selected for analysis (each line represents 14 infants). Blue = Endpoint Condition; Black = Starting Point Condition; Red = Within-Action Condition. On all graphs, positive orientation is up; x-axis is in milliseconds (ms) and y-axis is in microvolts (mV).

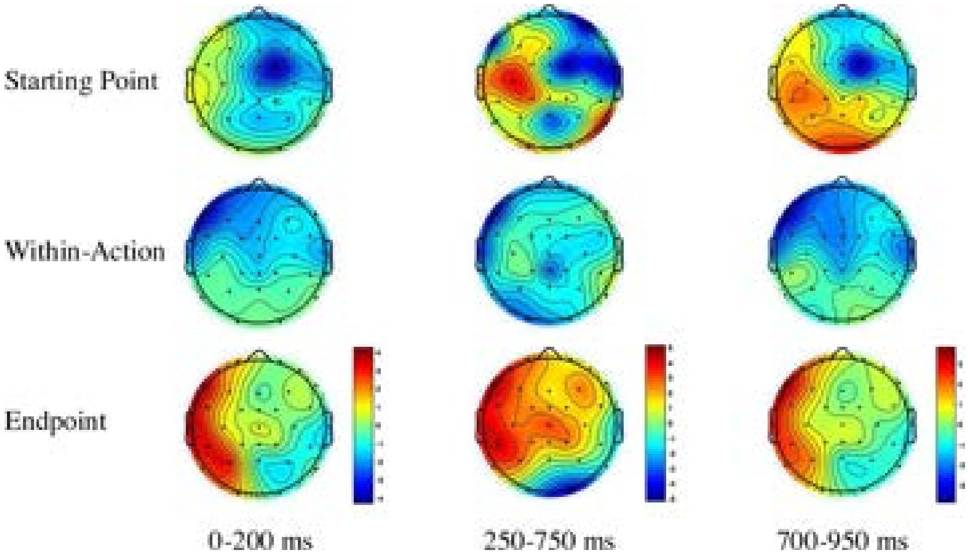

Fig. 3. Topographic plots for 10- to 11-month-old infants for all Conditions (Starting Point, Within-Action, Endpoint) within epochs of interest. Plots show values on a symmetrical scale generated from the greatest absolute value across maximum and minimum amplitudes.

($p =$ .0030); variance component = 9.64, SE = 3.24, 95 % CI [3.28, 15.98]. To further investigate this effect, we included Combination as a Between-Subjects factor reflecting which two conditions (out of 3) each participant observed: A (Starting Point, Endpoint); B (Within-Action, Endpoint), or C (Starting Point, Within-Action). This analysis corrected for the variance between conditions, and revealed that the interaction was driven by significant main effects of Condition for infants who observed Starting Point and Endpoint pauses [$F(1, 142.2) = 4.34$, $p =$ .039] and infants who observed Within-Action and Endpoint pauses [$F(1, 142.2) = 4.22$, $p =$ .041], but not infants who observed Starting Point and Within-Action pauses. Mean amplitudes for infants who observed Combination A were more positive for the Endpoint = .72 μV (SE = .72) than the Starting Point = −0.17 μV (SE = .72). Similarly, for Combination B, mean amplitudes were more positive for the Endpoint = −.001 μV (SE = .49) than the Within-Action pause = −1.12 μV (SE = .48).

3.3. Discussion

This study aimed to determine whether the infant brain is sensitive to endpoints within relatively unfamiliar, intransitive actions. To this end, we compared ERP responses as infants observed figure skating actions with uniform pauses inserted at starting points, endpoints, and within-action locations. We hypothesized that waveforms would reveal differential processing of pauses that occurred at the endpoints, compared with starting points or within-action locations. Although results identified a significant effect of Condition within the early epoch (0 − 200 ms), ERP responses differed from our predictions in two ways. First, follow-up analyses revealed that the effect of condition was driven by differences in response to pauses at endpoints when compared to pauses at within-action locations but no differences were observed between endpoints and starting points, or starting points and within-action locations. Second, ERP amplitudes were more negative in response to the within-action pauses, rather than the endpoint pauses as originally predicted.

These findings contrast somewhat with what we predicted based on robust behavioral evidence that endpoints are typically distinguished from starting points. One possibility is that starting points and endpoints were encoded similarly as “meaningful” boundaries to the action segment within this early epoch, particularly in the absence of other contextual cues such as a goal object/ location or source location. If this is the case, then the enhanced negativity to the within-action pauses may reflect infants’ sensitivity to disruptions occurring at unanticipated locations within continuous action (i.e., moments that do not typically coincide with a natural boundary or a perceived boundary). This interpretation is consistent with other work that has identified a similar effect in older children using goal-directed actions (Pace et al., 2013) and also resembles the N100 effect observed in adults thought to index aspects of visual attention related to task demands (Hillyard et al., 1998). Despite experimental controls, we cannot rule out the possibility that ERP effects within this early-latency window may have been influenced by differences in the perceptual features of the figure skater’s action during the pause.

Within the mid-latency epoch, findings were inconclusive. No significant main effects of the pause location were identified, however, differences were identified in the region involved, with waveforms in response to pauses in all conditions showing increased positive deflections that were maximal at frontal compared to posterior scalp locations. A negativity during this window would be suggestive of activation of attentional resources during observation of unfamiliar, intransitive motion events, but the positivity we observed cannot be reconciled with existing evidence. Although this effect was distinct from the condition-specific negativity that was expected, it suggests overall recruitment of electrophysiological resources during observation of unfamiliar dynamic stimuli depicting agentive action but lacking a physical goal object or location.

In our long-latency window, waveforms revealed more positive ERPs in response to pauses that occurred at endpoints when compared with pauses that occurred at within-action locations or starting points of the agent’s action, but these main effects were a function of the particular combination of pause locations viewed by the child. Specifically, differences between conditions emerged for infants who viewed pauses at the endpoint in combination with pauses located either at action beginnings or arbitrary locations within the action, but no differences for infants who observed pauses inserted at starting points and within-action locations. This is consistent with findings from Study 1, and supports the interpretation that pauses located at endpoints may have indexed memory encoding or updating processes in a way that was distinct from pauses at starting points or arbitrary within-action locations. Since the only feature that differed between conditions was the position of the pause, these results suggest that infants were not only sensitive to boundaries that coincided with action endpoints but may also rely on these moments to extract meaningful information regarding movement patterns that reflect action goals.

The present findings are among the first to provide electrophysiological evidence that infants’ ability to detect endpoints in continuous action may not be limited to object-directed motion but may also apply to dynamic human motion lacking tangible goal objects. Given the small sample size, the partial within-subjects design, and relatively few trials per condition, results should be interpreted with extreme caution. We address other methodological limitations as well as directions for future research in our general discussion.

4. General discussion

This work sought to further the field’s exploration of how endpoints might provide the figurative commas and periods that punctuate human action events for infants. We utilized two distinct methodologies to examine the nature of infants’ attention as they observed unfamiliar, intransitive human action in the form of figure skating performed by an international skating champion with pauses inserted at the starting point, endpoint, or within-action locations. First, we examined behaviorally whether infants’ visual attention to figure skating was differentially affected by artificial pauses inserted at one of these three locations. If infants were uniquely sensitive to endpoints as event boundaries, we reasoned that visual attention would be piqued when pauses disrupted the action at the endpoint within each event. With a separate group of infants, we compared electrophysiological responses to pauses inserted at these three locations. If infants were sensitive to the endpoints within unfamiliar intransitive actions (i.e., figure skating), we predicted that ERPs would reveal differential processing in response to pauses that occurred at the endpoint, when compared with pauses at the starting point or within-action locations.

The main finding of the present research is that across two studies using different methodologies, infants exhibited differential processing in response to pauses inserted at the endpoints of unfamiliar actions lacking a clear indicator of the action’s culmination. Results of both studies can be taken as preliminary evidence that infants may have distinguished the endpoints of figure skating actions from starting points and from other arbitrary moments within the segments. In Study 1, visual attention appeared to be greater for actions containing pauses at endpoints than for actions with pauses at starting points or actions with pauses occurring within action locations. Study 2 validated the behavioral findings of Study 1 by identifying differential ERP responses to artificial pauses depending on their placement. In particular, infants' electrophysiological activity, measured using ERPs, also distinguished endpoints from pauses at other locations, suggesting both rapid initial as well as extended processing of relatively unfamiliar, intransitive human action.

One explanation for infants' looking behavior and for ERP effects found within early and long-latency windows is that pauses inserted at endpoints *heightened* infants' attention. This possibility is supported by research examining action segmentation using a paradigm in which individuals "click through" a digitized video of an event; a measure of dwell time is produced for each digitized moment in the event. Given this individual-controlled task, participants, including adults and 3- and 4-year-old children, show significantly greater dwell times for action boundaries than for non-boundaries (Hard, Recchia, & Tversky, 2011; Meyer, Baldwin, & Sage, 2011). Similar logic has been used to explain why infants show a preference for speech in which artificial pauses are inserted at clause boundaries relative to speech in which inserted pauses interrupt clauses (Hirsh-Pasek et al., 1987). Consistent with this logic, findings from Study 1 and 2 suggest that action boundaries, and endpoints in particular, may recruit extra attentional resources for integrating all of the critical movements leading up to the culmination into a complete representation of the action.

Viewing pauses at the endpoint appeared to be critical in both studies. In Study 1, infants' visual fixations to skating events with pauses at endpoints were significantly different from those who viewed pauses at starting points and those who viewed pauses at within-action locations, but there were no differences in looking behavior between starting points and within-action locations. In Study 2, between-subject analysis revealed that pauses at endpoints appeared to require extended processing (after 700 ms) relative to pauses at either starting points or within-action locations; but no differences were identified when infants viewed only the starting point and within-action conditions.

Alternatively, it is also conceivable that when pauses at the endpoint aligned with infants' perceptions of where event boundaries should occur, these pauses may not have been noticed by infants, unlike pauses which did not align with infants' perceived boundaries. The broadly distributed negativity in response to pauses at within-action locations prior to 200 ms is consistent with this explanation: pauses that disrupted the continuous action at unexpected locations (arbitrary within-action locations) may have represented a greater structural mismatch compared with pauses that occurred at more naturalistic boundaries (i.e., endpoints) within this time window reflecting perceptual processing. Future research will be required to tease apart the possibility that infant attention was suppressed or enhanced by disruptions occurring at the endpoint, but the results nevertheless indicate that endpoints in intransitive action events are detected by 10- to 11-month-olds.

A necessary question to ask given these results is the following: What makes the endpoints of unfamiliar, intransitive human actions prominent? First, endpoints may be especially distinctive during action parsing because of their timing in the action sequence. Unlike starting points or any other part of an action, endpoints are present at a time when movements can be integrated into the whole sequence (Regier, 1997). For example, when observing a person sit down on the floor from a standing position, the person's initial movements may be ambiguous (e.g., is she picking something up off the floor? Is she stretching?). It is only when the end state is reached (i.e., the person sits) that earlier movements toward the intended goal (e.g., bending down) become meaningful. Consistent with this hypothesis, it has been shown that infants as young as 6 months (Kanakogi & Itakura, 2011) and even several great ape species (Kano & Call, 2014) attempt to visually predict the goals (i.e., outcomes) of human movements. These predictions suggest that throughout the observation of an action, individuals look ahead toward the endpoint to make sense of the observed movements, but the level of intentional understanding that guides this pattern of looking behavior is not at all clear.

A second possibility is rooted in infants' detection of low-level visual features that may also distinguish actions within each condition. Although each figure skating action differed only in the placement of the pause by condition, each action can be defined by a combination of cues such as velocity, configuration of limbs, rotation, and many other dynamic factors that vary along spatial or temporal parameters. As such, infants may have different visual experiences at the three stopping points, resulting in differential brain activity and looking times. It is likely that movement patterns within action segments played at least some role, given infants' proclivity for detecting statistical regularities within visual and auditory input (Buchsbaum, Griffiths, Plunkett, Gopnik, & Baldwin, 2015; Levine et al., 2019) and evidence that infants are tuned into properties of biological motion even when it is presented via point-light displays lacking any other contextual information (Bidet-Ildei, Kitromilides, Orliaguet, Pavlova, & Gentaz, 2013; Marshall & Shipley, 2009). Integrating behavioral approaches and brain-based measures with the *same* group of infants will be important for understanding the neural instantiation of infants' sensitivity to endpoints within different event types with varied cues to goal structure.

A third explanation for sensitivity to endpoints in motion events is the alignment of movement changes with the completion of goals that, together, contribute to coherent internal event structure. Although researchers examining adult event segmentation have demonstrated the unique influence of movements and intentions on event boundary perception (Zacks, 2004; Zacks, Kumar, Abrams, & Mehta, 2009), these factors may be inextricably linked (Baldwin & Baird, 2001) and may contribute to the perception of specific moments as "breakpoints" that define when one action ends and another begins (Hard et al., 2011). That is, the ending of a triple toe lutz reflects the completion of an intentional action and also reflects a unique combination of movement changes. This built-in redundancy may provide infants with a double clue as to where the endpoints of human action lie, enabling them to parse action at these moments. Indeed, some research has shown that when cues are in conflict (e.g., an actor moves toward an endpoint marked by a chair while looking *backward* toward the starting point marked by a stepstool), 4-year-olds no longer display a consistent visual preference for endpoints over starting points (Lakusta & Landau, 2012). Built-in redundancy may be behind how individuals segment the world in a variety of domains and may provide cues to how event representation emerges for linguistic and nonlinguistic stimuli alike. In language, for instance, infants may prefer to hear pauses at the end of clauses in continuous speech precisely because of the overlapping cues that mark these boundaries, from volume declination to final vowel lengthening (Hirsh-Pasek et al., 1987).

Although stimuli in the present research were nonlinguistic, findings have implications for the way in which infants come to acquire language that encodes event components. When describing a motion event, young children and adults typically encode the goal in a prepositional phrase, but often omit the source (Lakusta & Landau, 2012; Lakusta & Landau, 2005; Papafragou, 2010). For example, the preposition "FROM _" is more likely to be omitted than "TO _" in the following sentence: "The horse trotted [from the creek] to the barn" and this has been demonstrated typologically distinct languages including English, Spanish, and Greek. This linguistic preference to encode goal over source information is more consistent than the non-linguistic preference for endpoints over starting points, because it pertains to inanimate motion (e.g., a ball rolling off the table) in addition to animate, goal-directed motion (Lakusta & Landau, 2012). However, focusing on the highly interesting and socially relevant endpoints of human action may prepare infants for language, which similarly focuses on goals. Attention to endpoints may also help explain patterns described in linguistic development such as children's acquisition of transitive verbs earlier than intransitive verbs (Levi et al., 2014), and the tendency to interpret transitive verbs as referring to telic events that have a designated endpoint (Hohenstein, Naigles, & Eisenberg, 2004; Wagner, 2010). Links between semantic elements and syntactic structures are not always reliable, however, and research has yet to discover how infants construct flexible cognitive representations that encompass multiple nonlinguistic concepts relevant to motion events (e.g., agency, cause, intentionality, telicity), and explain how these features are expressed linguistically with attention to development and language-specific variation.

Several limitations constrain the generalizability of these findings. Study 1 used a between-subject design and would benefit from a replication in which each infant observes two or more pause locations in a within-subjects design. Similarly, in Study 2, infants' limited attention span required creative solutions to stimulus presentation such that infants never viewed the full combination of all three conditions. Rather, infants observed disruptions to a single location in our behavioral paradigm and a paired combination in our ERP paradigm. As actions necessarily unfold over time, this type of work must balance the need for a high number of trials with the variety and quantity of stimuli. The dynamic nature of our ERP stimuli as well as the insertion of artificial pauses within the continuous stream of action may have introduced additional noise and artifact into the data resulting in fewer acceptable trials for analysis. Human action in the real world, however, cannot always be simplified to the neat and tidy event structures that we often present in the laboratory; future research must balance the need for experimental control with ecological validity. Finally, we argue that individual differences in behavioral and electrophysiological responses warrant additional attention and should be interpreted as informative data rather than aberrations to eliminate.

This research speaks to the seemingly intractable process of transforming dynamic and fluid events into meaningful units of experience. Infants appear to use endpoints to naturally convert the continuous flow of information into discrete and categorical mental representations that may serve as a basis for interpreting complex and dynamic behavior. The present studies indicate that infants detect endpoints in a skilled performance event; yet, figure skating is still fairly controlled relative to the unpredictable vagaries of everyday action. Future research will be necessary to determine whether less skilled and possibly less constrained actions are processed in a similar manner. One central challenge is to pull apart infants' attention to actions expressed by intransitive compared to transitive frames and how this intersects with attention to semantic features like telicity (i.e., boundedness), causality, or agency. A comprehensive developmental story that describes links between infants' nonlinguistic event representations and the emergence of these syntactic structures and semantic components across languages would be of broad interest.

Moving forward, research relying on complementary behavioral and electrophysiological measures can further elucidate the processes underlying infants' action processing (Krogh-Jespersen, Filippi, & Woodward, 2014; Levine et al., 2019). Indeed, a thorough understanding of the ways in which infants' own experience observing and producing goal-directed action inform their experiences of the goals or endpoints that structure others' actions will necessarily integrate brain-based measures with behavioral methods to investigate development in relevant domains such as social cognition, motor skill, and language acquisition.

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CRediT authorship contribution statement

Amy Pace: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Dani F. Levine:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Roberta Michnick Golinkoff:** Conceptualization, Supervision, Writing - original draft, Writing - review & editing. **Leslie J. Carver:** Conceptualization, Resources, Supervision, Writing - original draft, Writing - review & editing. **Kathy Hirsh-Pasek:** Conceptualization, Resources, Supervision, Writing - original draft, Writing - review & editing.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.infbeh.2020.101425.

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