Kinematic Boundary Cues Modulate 12-month-old Infants' Segmentation of Action Sequences: An ERP Study

Matt Hilton[a*], Isabell Wartenburger[b] & Birgit Elsner[a]

[a]Department of Psychology, Cognitive Sciences, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany.

[b]Department of Linguistics, Cognitive Sciences, University of Potsdam,
Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany.

Author Note

This work was supported by a grant from the German Research Foundation (DFG, project number 258522519) within the Research Unit Crossing the Borders FOR 2253 to IW (WA 2969/7-1) and BE (EL 253/6-1).

Correspondence concerning this article should be addressed to Matt Hilton, Department of Psychology, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany.

Declarations of interest: none.

Cite this article as:

Hilton, M., Wartenburger, I., & Elsner, B. (2021). Kinematic boundary cues modulate 12-month-old infants' segmentation of action sequences: An ERP study. *Neuropsychologia.* https://doi.org/10.1016/j.neuropsychologia.2021.107916

Abstract

Human infants can segment action sequences into their constituent actions already during the first year of life. However, work to date has almost exclusively examined the role of infants' conceptual knowledge of actions and their outcomes in driving this segmentation. The present study examined electrophysiological correlates of infants' processing of lower-level perceptual cues that signal a boundary between two actions of an action sequence. Specifically, we tested the effect of kinematic boundary cues (pre-boundary lengthening and pause) on 12-month-old infants' ($N = 27$) processing of a sequence of three arbitrary actions, performed by an animated figure. Using the Event-Related Potential (ERP) approach, evidence of a positivity following the onset of the boundary cues was found, in line with previous work that has found an ERP positivity (Closure Positive Shift, CPS) related to boundary processing in auditory stimuli and action segmentation in adults. Moreover, an ERP negativity (Negative Central, Nc) indicated that infants' encoding of the post-boundary action was modulated by the presence or absence of prior boundary cues. We therefore conclude that 12-month-old infants are sensitive to lower-level perceptual kinematic boundary cues, which can support segmentation of a continuous stream of movement into individual action units.

Keywords: action segmentation; kinematic boundary processing; ERPs; boundary cues

https://doi.org/10.1016/j.neuropsychologia.2021.107916

1. Introduction

A critical stage in action processing is the segmentation of the individual actions out of a continuous stream of movement. From everyday actions like making a cup of coffee, to more skilled actions such as knitting, in order to understand or reproduce these action sequences, the constituent actions (e.g., taking cafetière from the cupboard, opening coffee jar, spooning coffee out) must be identified and encoded. A wealth of research has examined the cognitive processes that underlie action segmentation during infancy. In an influential study, Baldwin et al. (2001) presented 10- to 11-month-old infants with videos showing continuous everyday action sequences, and found longer looking times to videos that paused during ongoing actions than videos that paused following the completion of these actions (e.g., a pause during vs. after the grasp of a towel). This finding demonstrated that already by the end of the first year of life, infants represent ongoing actions and the boundaries between these actions as separate structural elements of an action sequence. The indication that infants associate action boundaries with moments of action completion has led some scholars to suggest that infants track actors' intentions and segment action sequences according to the fulfilment of related goals (e.g., Saylor et al., 2007). Such an account would posit that infants can rely on top-down processing, that is, the application of pre-existing knowledge and experience of actions, goals, and intentions to segment continuous motion into its constituent actions.

More recent work has suggested that action segmentation can also be supported by bottom-up processing of perceptual cues contained within the action stream, at least in adult populations. Studies of action production have revealed that boundaries in action sequences are marked by certain changes in kinematic properties of the movement forming the actions. For example, changes in motion velocity around a boundary (e.g., McAleer et al., 2014; Zacks et al., 2009) serve to lengthen the pre-boundary action and introduce a subsequent pause (i.e., a short absence of motion; Hilton et al., 2019). Adults make use of these kinematic boundary cues to segment observed action sequences, especially when top-down information relating to goal completion is not available. For example, when presented with a novel dance routine, participants with no dancing experience

https://doi.org/10.1016/j.neuropsychologia.2021.107916

reported pause detection as a strategy for determining the boundaries between individual dance moves (Bläsing, 2014). In another study, Hemeren and Thill (2010) asked adults to identify boundaries between individual actions of video-taped everyday action sequences (e.g., unscrewing a bottle cap) by button-press. Then, to restrict application of top-down processing to identify the boundaries, the videos were converted to moving constellations of light points and presented to another group of participants. Although the participants who viewed the light-point constellations were no longer able to determine the nature of the action sequences, they identified boundaries in the same locations as participants who saw the unconverted videos. This work neatly demonstrates that the movement stream must have contained lower-level perceptual kinematic boundary cues, which could be sufficient to support action segmentation in adults.

This previous work raises the critical question of how the bottom-up processing of kinematic boundary cues develops throughout infancy and early childhood. Existing work in this area has typically examined processing of naturally-produced action sequences performed by humans (e.g., Baldwin et al., 2001; Hespos et al., 2010; Saylor et al., 2007), meaning that effects of top-down and bottom-up processing cannot be disentangled. However, initial evidence for bottom-up processing in early action segmentation was presented in a recent study with 10- to 14-month-old infants, revealing differential processing of motionless pauses inserted within or at the boundary between human actions that were unfamiliar to the infants and did not involve attainment of object-related goals (i.e., Olympic figure skating; Pace et al., 2020). This study design meant, however, that these action sequences were also naturally-produced human action, making it difficult to fully exclude experience-based top-down processing, and meaning that these sequences were not controlled for the occurrence of kinematic boundary cues other than pauses.

The present study aimed to investigate bottom-up processing of kinematic boundary cues in infants' action segmentation. To this end, the work was guided by potential parallels between speech and action processing, and aimed to extend existing research that has sought to isolate the bottom-up processes driving speech segmentation during infancy. As continuous information streams that can be organized hierarchically, action sequences and speech share structural similarities (Zacks, 2004). Speech segmentation can be driven by top-down knowledge-based processing, but infants initially capitalize on bottom-up cues embedded in prosody to determine boundaries between words and phrases in speech (e.g., Christophe et al., 2003). Three such prosodic boundary cues in several languages are silent pauses, lengthening of the pre-boundary material, and pre-boundary pitch-rise (e.g., Hockey & Fagyal, 1998; Peters, 2005; Tyler & Cutler, 2009). Furthermore, while infant-directed speech has been found to exaggerate prosodic boundary cues (e.g. Church et al., 2005), infant-directed action (also known as *motionese*; Brand et al., 2002) is characterised by an increase in frequency and duration of pauses, as well as increased duration of actions (Fritsch et al., 2005; Rohlfing et al., 2006), which could reflect an exaggeration of the kinematic boundary cues pause and pre-boundary lengthening. Drawing on arguments that infant-directed speech supports infants' speech processing by facilitating speech segmentation in certain language populations (Thiessen et al., 2005; Floccia et al., 2016), it is plausible that motionese supports infants' action processing by facilitating action segmentation, warranting a more fine-grained examination of infants' processing of kinematic boundary cues. A well-established method for studying the processing of prosodic boundary cues in speech segmentation is EEG. For example, Holzgrefe-Lang et al. (2018) presented 6- to 8-month-old infants raised in German-speaking households with spoken sequences consisting of three proper names coordinated by *und* ("and"; e.g., "Mona und Lilli und Lola"). Critically, the sequences did or did not contain an internal grouping, which was marked by prosodic boundary cues (i.e., lengthening of the pre-boundary syllable, a rise of pitch at the second name, and the insertion of a subsequent pause). The onset of the prosodic boundary cues evoked a broadly-distributed slow-forming positivity in the event-related potential (ERP) which continued until the onset of the post-boundary word. This positivity was understood as an example of the Closure Positive Shift (CPS; Steinhauer et al., 1999), a well-established ERP marker of prosodic boundary processing in adults (e.g., Holzgrefe et al., 2013; Pannekamp et al., 2005) and children (Männel et al., 2013; Männel & Friederici, 2016).

https://doi.org/10.1016/j.neuropsychologia.2021.107916

The CPS in adults has also been found in response to pre-boundary lengthening and pauses in non-speech auditory streams of information such as music (Glushko et al., 2016) or hummed speech (Pannekamp et al., 2005). These findings suggest that the CPS is not a language-specific marker of boundary processing, and have led some scholars to conclude that the component reflects domain-general cognitive processes involved in the segmentation of continuous streams of information (e.g., Gilbert et al., 2015). As further support for this assumption, recent work found an ERP positivity in response to kinematic boundary cues (i.e., pre-boundary lengthening, pause) embedded in visual sequences of hand actions performed on a ball with no discernible goal (e.g., sliding, shaking, lifting; Hilton et al., 2019). This ERP positivity was similar in spatial distribution and timing to the CPS. This work with adults thus identified pre-boundary lengthening and pause as kinematic boundary cues that signal the location of a boundary in an action sequence, and suggested the CPS as a candidate ERP component that reflects adults’ and potentially infants’ processing of these cues.

Another ERP component that has been related to infants’ action processing is the Negative Central (Nc) component, characterised as a negative peak over fronto-central electrodes, emerging between 300 and 900 ms following the onset of a visual stimulus (e.g., Nelson & Collins, 1991; Reynolds & Richards, 2005). The Nc is regarded as a measure of attention and memory activation during the first year of life (e.g., Richards et al., 2010; Reynolds & Richards, 2019), with a larger Nc amplitude reflecting greater engagement to and thus encoding of a visual stimulus. Nine-month-old infants showed a larger Nc amplitude to familiar than novel actions, probably reflecting greater allocation of attentional resources (e.g., Kaduk et al., 2016). Similarly, Schönebeck and Elsner (2017) found an Nc-like negativity in 14-month-old infants in response to images of an action outcome (e.g., hands holding two separated halves of a dumbbell; Meltzoff, 1995), with the negativity being larger when infants had witnessed actions after which this outcome was expected (i.e., attempts to pull the dumbbell apart) rather than unexpected (i.e., an action that could not have resulted in the dumbbell’s separation). Taken together, these findings suggest that infants allocate greater attentional processes to familiar or expected actions and action outcomes, in this case reflected by larger Nc amplitudes. Conversely, Pace et al. (2013) presented 24-month-old infants with videos of interrupted and uninterrupted action sequences, and found a relatively larger ERP negativity in the 300-600 ms time window in response to interrupted sequences, which they interpreted as evidence that these infants devoted more attention to the interrupted than uninterrupted action sequences. In line with work examining the Nc in response to familiar and unfamiliar pictures (e.g., de Haan & Nelson, 1997; Reynolds & Richards, 2019), these examples show that it is sometimes difficult to predict whether infants will allocate more attention to familiar and expected or unfamiliar and unexpected actions or action outcomes, a difficulty which is further compounded by differences in study design, age of sample, and stimuli in this previous work.

In a more recent study that examined the Nc specifically in the context of action segmentation (Monroy et al., 2019), 8- to 11-month-old infants were trained by watching continuous sequences of pairs of goal-directed actions performed on a novel mechanical toy (e.g., sliding a switch, twisting a joystick). Some action pairs exerted a subsequent effect (i.e., a lamp illuminating after completion of the second action), but other pairs did not. A test phase followed, during which the infants were presented with sequences of two images, each depicting the mid-point of an action seen during training. The sequences were composed of either intact action pairs that had been presented during training, or deviant pairs consisting of previously-seen actions that had not been paired during training. The authors found an Nc in response to the second action of all pairs, demonstrating that the Nc component can be evoked by individual actions of an action sequence. Furthermore, the amplitude of the Nc was greatest in response to the second action of a deviant pair when the first action had been part of an action pair that triggered an action effect during the training phase. To explain this finding, the authors speculated that the infants could have chunked, or formed a single segment of, the two actions of those pairs that exerted an effect. Thus, the enhanced Nc could have reflected that observing the first action triggered an expectation regarding the second action of the pair, which was violated by the second, deviant action.

Irrespective of theoretical implications, these findings demonstrated that differences in Nc amplitude are a useful measure by which to examine infants' processing of individual actions in an action sequence. Building on this work, we therefore elected to adopt the Nc as a candidate component by which to examine infants' bottom-up processing of kinematic boundary cues: If infants make use of kinematic boundary cues to determine the structure of action sequences, it would be expected that their processing of an action following these cues would differ from an action in the same position that is not preceded by kinematic boundary cues. Thus, the Nc could indicate whether infants process an action as either a continuation of the current action segment, or the initial action of a new segment.

The purpose of the current study was two-fold. First, we wanted to determine whether ERP components indicate that infants can detect kinematic boundary cues in an action sequence already by the end of the first year of life. Second, to determine that the processing of these cues supports infants' action segmentation, we investigated whether kinematic boundary cues would modulate the ERP response to a subsequent action. We therefore recorded ERP activity while 12-month-old infants watched sequences of actions that did or did not contain kinematic boundary cues. In order to be able to single out the contribution of bottom-up processing, and to accurately control the timing and movement of the actions, we followed previous work into action processing (e.g., Twomey et al., 2014) by presenting infants with videos of an animated character performing arbitrary sequences of three whole-body actions (i.e., turning, stretching, lifting). On no-boundary trials, the three actions were performed as a single continuous sequence with no kinematic boundary cues present, whereas on boundary trials, a boundary was marked by pre-boundary lengthening of the second action and a pause between the second and final action. In naturally-occurring action sequences, the duration of kinematic boundary cues are relatively brief, but EEG's high temporal resolution meant that online processing of these cues could be recorded. If the 12-month-old infants were sensitive to the presence of these kinematic boundary cues, we should find a boundary-related CPS-like positivity between the second and third actions on boundary trials (cf. Hilton et al., 2019;

Holzgrefe-Lang et al., 2018). We also examined attention to and encoding of each action in the sequence as reflected by the Nc component. If kinematic boundary cues affected infants' processing of the subsequent action, we would expect between-condition differences in the Nc response to the third action.

2. Method

2.1 Participants

The final sample included twenty-seven 12-month-old infants (M_{age} = 11.7 months; *SD* = 0.7; 13 girls). All children were full-term, typically-developing, and monolingual from German-speaking households. Additionally, fourteen 12-month-old infants were tested but their data were not included in analyses due to refusal to wear the EEG cap (*n* = 3), technical problems (*n* = 6), the participant not meeting sample inclusion criteria (infant raised in bilingual environment; *n* = 1), or attention to the screen did not meet a threshold of 12 trials per condition (*n* = 4). Participants were recruited from a database of families who had previously indicated interest in taking part in such studies. Parents provided written informed consent, and travel costs were reimbursed. The study was approved by the ethics committee of the University of Potsdam.

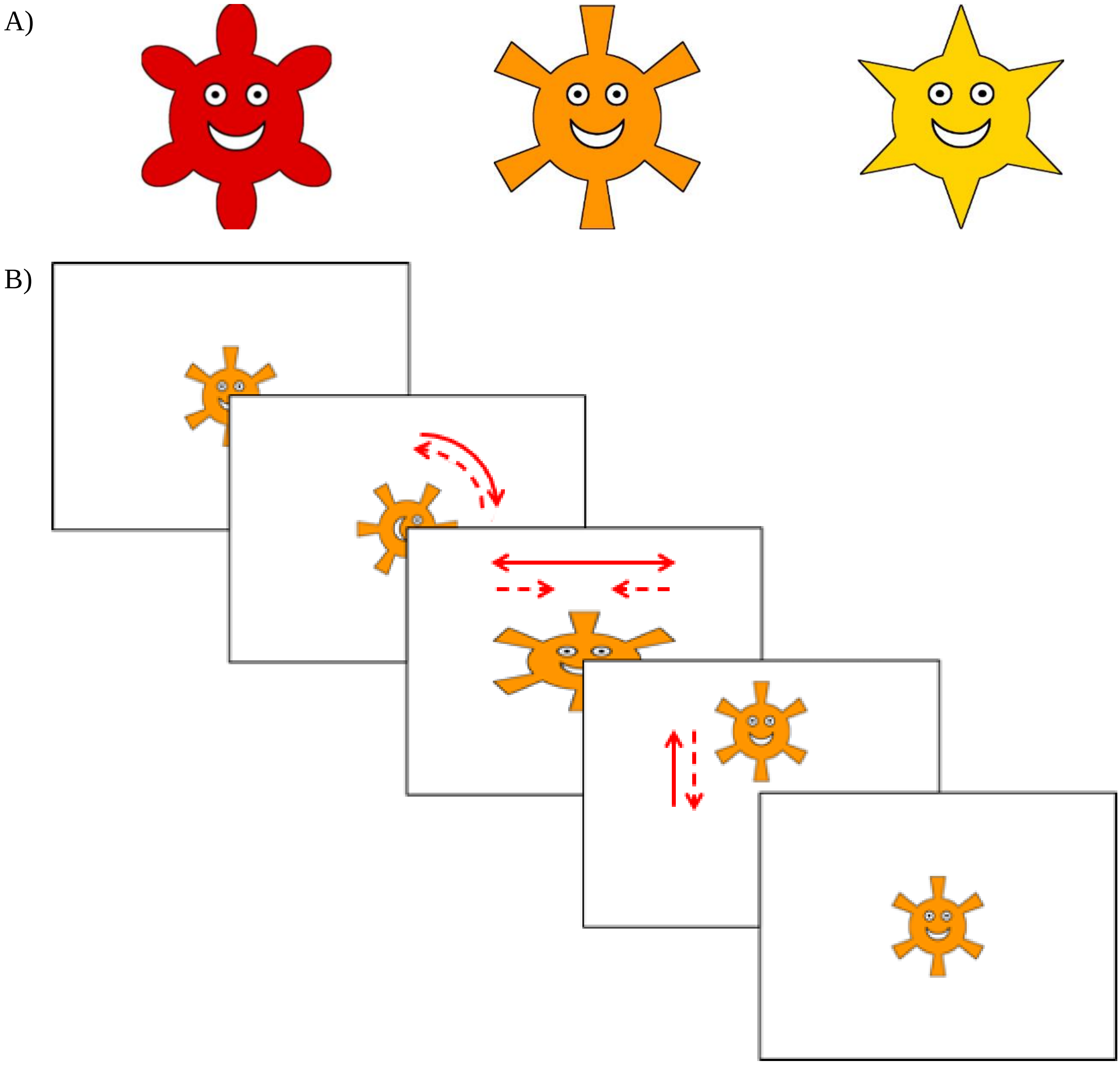
2.2 Stimuli

Stimuli consisted of a series of videos. Each video showed one of three cartoon characters of similar shape with a smiling face located in the centre of a white background. In each video, the character moved across the screen to demonstrate three distinct actions. Three characters differing in colour and shape of extremities (see Figure 1, panel A) were designed to increase the interest of the videos, but the actions were identical across characters. Each video began with the character appearing on the screen and remaining stationary for 1,000 ms. As shown in Figure 1B, the three actions consisted of rotating 90° clockwise and back (*turning*), expanding in the horizontal plane and then returning to original size (*stretching*), and travelling upwards then downwards (*jumping*). These actions were designed to ensure that following the completion of each action, the character returned to the same location on the screen. These stimuli also allowed full control of the speed, onset, and offset of each action, meaning that we could ensure that any differences between conditions were due to the specific cues under consideration.

Twelve videos were created in which each of the three characters performed each of two action sequences: *turning, stretching, lifting* and *lifting, stretching, turning*. Each action sequence was created for two conditions: In the no-boundary condition, all three actions were presented as one continuous sequence. In the boundary condition, kinematic boundary cues were added between the second and final action by inserting a motionless pause and lengthening the second, pre-boundary action relative to the corresponding action in the no-boundary condition. The second action was *stretching* on all trials, and pre-boundary lengthening was achieved by slowing down the second phase of the action (as the character was returning to its original size), meaning that timing of stimuli in both conditions was identical until the mid-point of the second action. Each video began with a 1,000 ms interval in which the character was static in the center of the screen, before moving to begin the action sequence. The timings of the actions can be seen in Table 1. Due to technical problems, the pause in the boundary videos showing the orange sun-shaped character (i.e., one third of boundary-condition trials) was 400 ms longer than in other boundary videos. Overall duration of videos in the no-boundary condition was 2,950 ms, and in the boundary condition was 3,540 ms with the shorter pause (two thirds of the trials) and 3,940 ms with the long pause (one third of the trials). Visual inspection revealed that ERPs to the final action did not differ between videos with a shorter pause or a long pause, so all analyses reported in this paper include both short- and long-pause boundary condition videos. For analyses excluding these trials with identical results, please consult the supplementary material.

Figure 1

A) Animated characters shown in the study. B) Schematic of an example trial. Durations of individual actions are shown in Table 1.



Note. In panel B, the solid red arrow denotes the first phase of the action. The dashed red arrow denotes the second phase of the action, during which the character returns to its original state.

Table 1

Durations of actions in the two conditions (ms)

		No-boundary condition	Boundary-condition
Action 1 (*turning / lifting*)	Phase 1	300	300
	Phase 2	300	300
Action 2 (*stretching*)	Phase 1	300	300
	Phase 2	300	540
Pause		0	350
Action 3 (*lifting / turning*)	Phase 1	375	375
	Phase 2	375	375

Note. Each action consisted of two phases: The first phase consisted of the character transforming away from its original state (e.g., stretching outwards), and the second phase followed completion of the transformation and consisted of the character returning to its original state (e.g., contracting back to its original size). Due to technical issues, the pause was 750 ms in duration in one third of the boundary trials (long-pause trials). This longer pause had no systematic effects on the results (see supplementary material).

2.3 Procedure

In an electrically-isolated chamber, infants were seated in a high chair in front of a computer screen upon which the stimuli were presented, and parents sat on a chair behind their child. Parents were instructed not to interact with their child during stimulus presentation, and researchers ensured that this instruction was complied with by monitoring the session via a camera. Testing was paused if the child became restless. Using Presentation software (version 19.0, Neurobehavioral Systems, www.neurobs.com), the 12 video stimuli were repeatedly presented in a random order until the infant became too restless to continue participating.

2.4 EEG Recording and Pre-processing

EEG was recorded at 1,000 Hz from 32 active Ag/AgCl electrodes (actiCap, Brain Products, Germany), with electrodes placed according to the international 10-20 system (American Clinical Neurophysiological Society, 2006). EEG recording was referenced online to the right mastoid, and then re-referenced offline from the average of the two mastoids. Impedances were kept below 20 kΩ.

The EEG signal was pre-processed in Brain Vision Analyzer (Version 2.1; Brain Products, Gilching, Germany). A digital bandpass filter ranging from 0.3 to 50 Hz was applied with a 50 Hz notch filter. Epochs from the onset of the first action to the offset of the final action were defined, and the signal in each epoch was corrected to a baseline in the 300 ms interval following the onset of the video when the onscreen character was motionless (prior to the first action). Data were ocular corrected using the Gratton and Coles method (1983) seeded from electrodes Fp1 and Fp2. Infants were presented on average with 37 trials (*SD* = 6.43) in the no-boundary condition and 38 trials (*SD* = 6.02) in the boundary condition before the experimenter ended the experiment. In line with previous infant ERP work, analysis of the CPS (Holzgrefe-Lang et al., 2018) included data from 9 critical electrodes, grouped into three regions of interest: frontal (F3, Fz, F4), central (C3, Cz, C4), and posterior (P3, Pz, P4), and analysis of the Nc was restricted to electrodes in the frontal and central regions (F3, Fz, F4, C3, Cz, C4; Monroy et al., 2019). The epochs at these channels were searched for artefacts (rejection criteria based on Holzgrefe-Lang et al., 2018: maximal allowed voltage step: 50 µV; maximal allowed difference in 100 ms intervals: 200 µV; minimal/maximal allowed amplitude: ±200 µV; lowest allowed activity in 100 ms intervals: 0.5 µV), and trials were visually inspected for the presence of artefacts. Epochs containing artefacts were excluded from analyses.

To be included in analyses, infants were required to contribute data from at least 12 trials in each condition. An independent samples *t* test revealed that infants contributed a comparable number of artefact-free trials in the boundary condition (*M* = 23.80; *SD* = 5.86; range: 15-34) and in the no-boundary condition (*M* = 25.60; *SD* = 5.50; range: 15-37), *t* (26) = -1.57, *p* = .13, *d* = 0.30. Slightly, but significantly more trials were discarded because infants looked away from the screen during the action sequence in the boundary condition (*M* = 13.7 trials, *SD* = 4.45, range = 0 – 20) than in the no-boundary condition (*M* = 11.5 trials, *SD* 4.59, range = 5 – 23), *t* (26) = 2.23, *p* = 0.034, *d* = .43, likely because the boundary trials were longer which gave infants a greater opportunity to look away. The epochs were exported for analysis and graphing in R (version 3.6.2) via RStudio (version 1.2.5001; R Core Team, 2019). The specific time window in which analysis was performed varied across analyses (see below). All ANOVAs were performed using the "ez" package (version 4.4-0; Lawrence, 2016), and in cases of sphericity assumption violation, Greenhouse-Geisser corrected *p*-values are reported. Bonferroni correction was applied to *p*-values obtained from post-hoc paired comparisons. Data were plotted using the "ggplot2" package (Wickham, 2016).

2.5 Data Analysis

The first aim was to examine whether the onset of the boundary cues in the boundary condition evoked a CPS-like positivity in the ERP relative to the no-boundary condition. Previous analyses of this component with auditory stimuli have typically time-locked the ERPs in both conditions to the time at which the boundary cues emerges in the boundary condition, and then compared mean amplitude in a following time interval ranging between 100 ms (Knösche et al., 2005) to 500 ms (Pannekamp et al., 2005). Holzgrefe-Lang et al.'s (2018) examination of the CPS in infants using auditory name sequences, for example, examined mean amplitude in a 300 ms time window following the offset of the pre-boundary word. However, visual inspection of the ERP in Figure 2 indicated that for our visual stimuli, this time interval included a large negative peak in both conditions (which could be an Nc component related to the second action; see below). In the no-boundary condition, this negative peak was followed by a further negative peak (albeit smaller in magnitude), related to processing of the final action. Mean amplitude would therefore be an inappropriate measure of boundary-cue processing with our visual stimuli, because it would be impossible to conclude whether a difference was due to a positivity in the boundary condition, or the negative peaks in the no-boundary condition. We therefore opted instead to take as our measure mean maximum amplitude in the epoch from the mid-point of the second action, when pre-boundary lengthening emerged in the boundary condition, until the mid-point of the final action (i.e., analysis interval duration per condition: no-boundary = 675 ms, boundary with short pause = 1,265 ms, boundary with long pause = 1,665 ms). We calculated maximum amplitude for each epoch, and averaged this value across participants, condition and region. This measure allowed us to examine whether infants' ERP in the boundary condition became more positive in response to the boundary cues than would be expected if the boundary cues were not present (i.e., in response to the offset of the second action in the no-boundary condition).

The second aim was to examine whether differences in Nc magnitude occurred between conditions according to the position of the action in the sequence (first, second, or final). This would indicate whether the presence of kinematic boundary cues in the boundary condition affected infants' processing of the subsequent action relative to actions at the same position in the no-boundary condition (e.g., Kaduk et al., 2016; Pace et al., 2013; Schönebeck & Elsner, 2017). We therefore analysed ERP negativity to actions performed by the animated character in the absence of kinematic boundary cues (the first action), when pre-boundary lengthening did or did not occur (the second action), and to actions following or not following the pre-boundary lengthening and pause (the final action). In line with previous work examining the Nc in a context of infants' action processing (e.g., Monroy et al., 2019), we exported epochs in a time window of 250-750 ms following the onset of each action (first, second, and final). We calculated minimum amplitude for each epoch, and averaged this value across participants, condition and action.

3. Results

3.1 Boundary-related Positivity Analysis

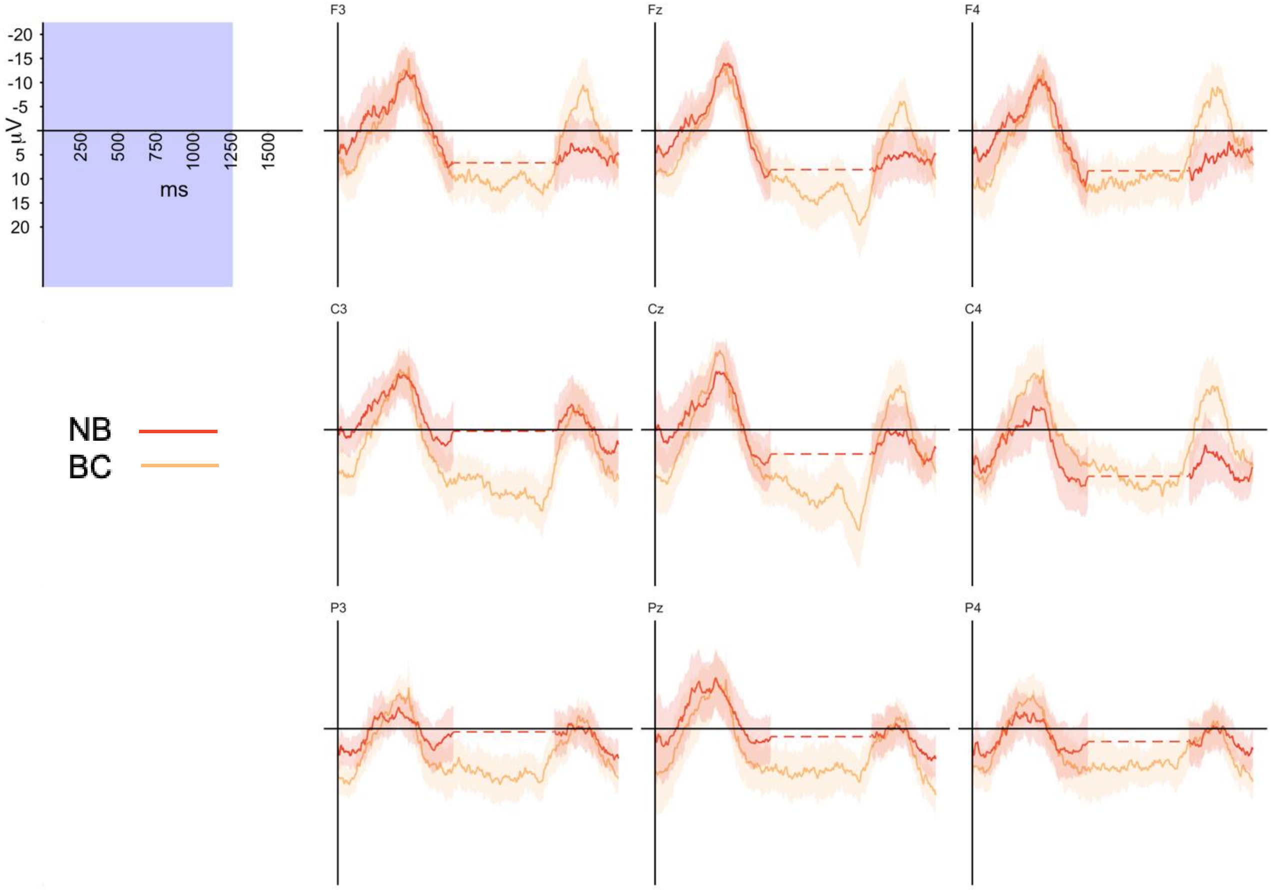
A 3 (region: frontal, central, posterior) x 2 (condition: boundary, no-boundary) repeated-measures ANOVA on the mean maximum amplitude from all electrodes of interest revealed a significant main effect of condition, F (1, 26) = 73.11, $p < .001$, $\eta_G^2 = 0.34$, resulting from a larger positivity in the boundary condition (M = 75.32 μV, SD = 13.91) than in the no-boundary condition

https://doi.org/10.1016/j.neuropsychologia.2021.107916

(*M* = 56.15 µV, *SD* = 11.19; Figure 2) across all electrodes. A significant main effect of region was also found, *F* (2, 52) = 19.08, *p* < .001, η_G^2 = 0.065, and post-hoc tests revealed no difference between frontal (*M* = 69.09 µV, *SD* = 12.99) and central location (*M* = 67.24 µV, *SD* = 10.31; *p* = .72) across conditions, but a larger positivity in frontal (*p* < .001) as well as in central (*p* < .001) than posterior location (*M* = 60.88 µV, *SD* = 12.40). No significant interaction was revealed, *F* (2, 52) = 2.70, *p* = .077, η_G^2 = 0.0038, confirming our prediction that the condition difference, with a larger positivity in the boundary condition, was broadly distributed. These results were identical when excluding trials with the long pause (see supplementary material).

Figure 2

Grand average ERPs for the across representative electrodes in the no-boundary (NB; dark orange) and boundary (BC; light orange) conditions time-locked from the midpoint of the second action to the offset of the final action.



Note. Following EEG convention, the y-axis is plotted with negative upwards. The analysis interval is shaded light blue (from the midpoint of the second action to the midpoint of the third action). The interval for baseline correction was 0 to 300 ms relative to the onset of the stimulus video (prior to the first action). Shaded errors around the mean represent 95% CIs, corrected for within-subject comparisons by the Cousineau-Morey method (Morey, 2008; Craddock, 2016) where applicable. Given the presence of pre-boundary lengthening and the pause in the boundary-condition, epochs in this condition are longer than in the no-boundary condition. To illustrate the data that were entered into our analysis, we have shifted the ERP in the no-boundary condition so that only data taken into account for the analysis are included in the shaded blue box, and the resulting "gap" in the no-boundary condition has been filled with a dotted line. For presentation purposes only, data from boundary trials with the longer pause are excluded.

3.2 Nc Analysis

A 3 (action: first, second, final) x 2 (condition: boundary, no-boundary) repeated measures ANOVA was performed on the mean Nc peak amplitude data. The analysis revealed no significant main effect of condition, F (1, 26) = 0.65, p = .43, $\eta_G^2 = 0.0031$, but a significant main effect of action, F (2, 52) = 4.16, p = .021, $\eta_G^2 = 0.021$, which was qualified by a significant interaction of condition and action, F (2, 52) = 7.73, p = .001, $\eta_G^2 = 0.026$. Post-hoc tests revealed no significant difference between conditions during the first action (mean difference = 2.02 µV, SD = 10.20; p = .94) or second action (mean difference = 0.46 µV, SD = 8.65; $p > .99$), but, as expected, a significantly larger Nc amplitude in the boundary than no-boundary condition during the final action that followed the kinematic boundary cues (mean difference = -6.02, µV, SD = 11.00; p = .025) [1]. As can be seen in Figure 3, in the boundary condition, an Nc of similar amplitude was

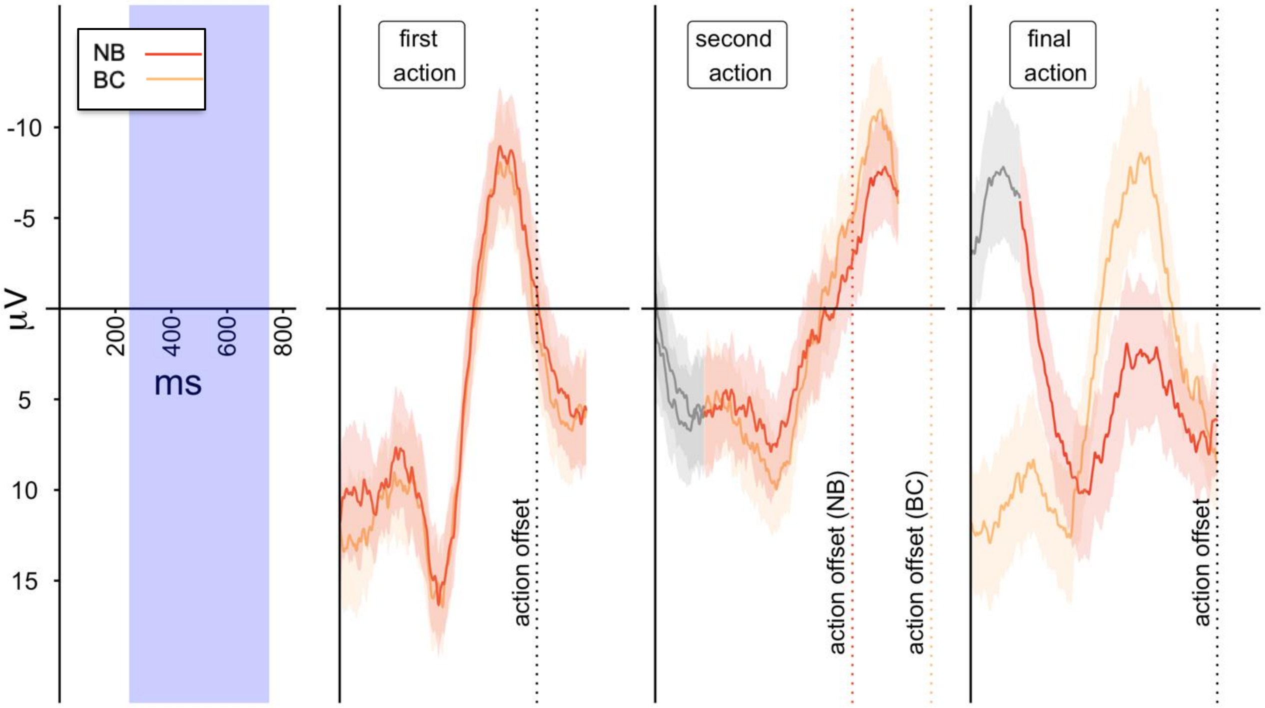
---

[1] The onset of the final action in the no-boundary condition was followed almost immediately by a large negative peak, and we contend that this peak was the offset of the Nc response to the second action. Given that this peak occurred so soon after action onset (approx. 50 ms), it is unlikely that this peak was related to processing of the final action.

evoked by all three actions, F (2, 52) = 1.22, p = .30, η_G^2 = 0.012. However, in the no-boundary condition, Nc amplitude differed across actions, F (2, 52) = 11.27, p = < .001, η_G^2 = 0.076, meaning that Nc amplitude did not differ between first and second actions (p > .99), but was significantly smaller in the final action than in both the first (p = .021) and second action (p < .001). These results reveal that the interaction was driven by a larger Nc amplitude when the final action followed the kinematic boundary cues than when the action in the same position was not preceded by kinematic boundary cues.

Figure 3

Grand average ERPs across fronto-central electrodes in the no-boundary (NB; dark orange) and boundary (BC; light orange) conditions, time-locked to the onset of the first, second, or final action.



Note. Following EEG convention, the y-axis is plotted with negative upwards. The analysis interval is shaded light blue (250-750 ms following action onset). The interval for baseline correction was 0 to 300 ms relative to the onset of the stimulus video (prior to the first action). Shaded errors around the mean represent 95% CIs, corrected for within-subject comparisons by the Cousineau-Morey method (Morey, 2008; Craddock, 2016).Vertical dotted lines represent the offset of the action, and

https://doi.org/10.1016/j.neuropsychologia.2021.107916

due to pre-boundary lengthening the length of the second action differs between the no-boundary condition (dark orange dotted line) and boundary condition (light orange dotted line). Given that the Nc analysis window sometimes overlaps the onset of the following action, some data are duplicated across panels. Data that are duplicated from a previous panel are shown in grey.

4. Discussion

The current study examined the effect of two kinematic boundary cues, pre-boundary lengthening and pause, on 12-month-old infants' processing of an action sequence. Infants were presented with videos in which an animated character performed a sequence of three actions, with or without kinematic boundary cues to mark a boundary between the second and third action. ERP activity was recorded while infants viewed these sequences, and analyses revealed that the onset of kinematic boundary cues evoked a positivity in the ERP, similar to the CPS typically found in adults' and infants' speech segmentation (e.g., Holzgrefe-Lang et al., 2018). We also found evidence that kinematic boundary cues modulated infants' processing of the action that followed the kinematic boundary cues: Relative to the same action when preceded by these cues, the Nc to the final action was larger in the boundary condition than in the no-boundary condition.

The finding of an ERP positivity in response to the kinematic boundary cues is in line with recent work that presented adult participants with sequences of three naturalistic actions, and found a broadly-distributed positivity in the ERP, beginning at the onset of the kinematic boundary cues and enduring until the onset of the post-boundary action (Hilton et al., 2019). In terms of infants' detection of kinematic boundary cues, the present finding suggests that the cognitive processes that support the processing of these cues are active already during the first year of life. Furthermore, the 12-month-old infants' ERP positivity in the boundary condition shared temporal and spatial characteristics with the CPS found in response to prosodic boundary cues in speech at 6 months of age (Holzgrefe-Lang et al., 2018), adding further weight to arguments that the cognitive processes driving the CPS are domain-general (Gilbert et al., 2015; Glushko et al., 2016; Hilton et al., 2019; Knösche et al., 2005). Moreover, previous research has concluded that infants and young children are sensitive to the location of boundaries between actions in naturally-produced action sequences performed by humans, and that these action boundaries are highly salient when the actions are familiar and goal-directed (Baldwin et al., 2001; Meyer et al., 2011; Pace et al., 2020; Saylor et al., 2007). These findings have been attributed to top-down processing of the fulfilment of action goals, which enables segmentation of continuous motion into its constituent actions (e.g., Baldwin et al., 2001). The current study extends this previous work by demonstrating that 12-month-old infants are sensitive to the low-level perceptual kinematic cues to boundaries in arbitrary sequences of three whole-body actions performed by an animated character. A bottom-up detection of these kinematic boundary cues may therefore drive infants' processing of action boundaries, even when access to top-down conceptual knowledge is not yet available or is not triggered when observed actions do not result in discernible action goals.

The current study also examined whether 12-month-old infants' bottom-up processing of the kinematic boundary cues supported action segmentation, as indexed by modulation of infants' processing of the following action. To do this, we compared ERP activity in a time window of 250-750 ms following the onset of each action, thereby analysing the amplitude of the Nc. The Nc is a marker of infants' attention to and encoding of a stimulus (Richards et al., 2010; Reynolds & Richards, 2019) and has recently been implicated in infants' encoding of actions and their outcomes (Kaduk et al., 2016; Pace et al., 2013; Schönebeck & Elsner, 2017) as well as of individual actions of an action sequence (Monroy et al., 2019). The present results confirmed our expectation that the onset of both the first and second action would evoke comparable Nc responses in both conditions, because the conditions only began to differ towards the end of the second action. This finding suggests that infants encoded the first and second action of the sequences similarly in both conditions. The results also matched our expectation of a condition difference for the Nc to the final action, and we found this Nc to be larger in the boundary condition than in the no-boundary condition.

Based on existing evidence that differences in Nc amplitude reflect differences in infants' processing of actions and action outcomes (Kaduk et al., 2016, Monroy et al., 2019), our findings indicate that the 12-month-old infants' encoding of the final action depended on the presence or absence of preceding kinematic boundary cues. However, taking account of the Nc response to all three actions of the sequence across conditions precludes a straightforward explanation of these results. It could have been expected that a larger Nc response to the final action in the boundary condition would indicate that the infants processed the final action in this condition as the initial action of a new segment, while the absence of kinematic boundary cues led infants to perceive the final action in the no-boundary condition as belonging to the same segment as the second action (cf. Monroy et al., 2019). This interpretation does not, however, explain the finding that the final action in the boundary condition evoked an Nc response that did not differ from the response to the first and second actions, across conditions. One speculative explanation could be that infants began processing the sequence as a single segment only after encoding the first and second action individually, as evidenced by the similar Nc responses to these actions. Such an explanation could be supported by work on speech segmentation, which suggests that adult participants begin segmenting an ongoing sequence at the offset of the second unit of a segment, but not after the first unit (Holzgrefe et al., 2013). We cannot, however, exclude the alternative explanation: that our Nc results were due to the absence of kinematic boundary cues in the no-boundary condition, rather than the insertion of kinematic boundary cues in the boundary condition. It is plausible that the 12-month-old infants' cognitive capacity was overloaded by processing the sequence of three arbitrary actions, and so their encoding of the final action in the no-boundary condition was weakened, resulting in a muted Nc. In the boundary condition however, the kinematic boundary cues could have prompted infants to encode and store the previous two actions as a single segment, freeing up capacity to then fully encode the final action. Given the novelty of the current study, it was to be expected that the results would require follow-up work, for example by examining infants' processing of kinematic boundary cues in sequences of more than three actions.

Previous work probing the presence of the CPS has compared the average amplitude during the time of the boundary in the boundary condition with the comparable time frame in the no-boundary condition (e.g., Hilton et al., 2019). In the present study, this analysis procedure was not suitable because the transition between the second and third action in the boundary condition was marked by a slowly-emerging positivity, while the comparable time frame in the no-boundary condition was marked by the unfolding of a negativity (i.e., Nc component) to the final action's onset. Therefore, we opted to examine the CPS by analysing maximum amplitude from the mid-point of the second action to the mid-point of the third action, which revealed a larger positivity in the boundary condition. Given this subtle difference in analysis, it would be important to further examine the nature of the boundary-related positivity in studies on adults' and infants' segmentation of action sequences.

Taken together, the findings of the current study extend our understanding of early action processing by showing that infants, like adults, are sensitive to kinematic boundary cues, which may be sufficient for action segmentation especially when top-down information about goal completion is not available (Bläsing, 2014; Hemeren & Thill, 2010). Boundaries between actions are typically accompanied by changes in motion velocity (e.g., McAleer et al., 2014; Zacks et al., 2009), and the present findings reveal that infants' processing of these kinematic boundary cues is reflected in ERP responses similar to those found during infants' and adults' speech segmentation (e.g., Holzgrefe-Lang et al., 2018; Steinhauer et al., 1999) or infants' chunking of action segments in an ongoing goal-directed action sequence (Monroy et al., 2019). Critically, in naturally-produced action sequences performed by humans, kinematic boundary cues typically co-occur with the attainment of action goals, meaning that it is difficult to disentangle the impact of perceptually-driven bottom-up processing and conceptually-driven top-down processing in infants' action segmentation (Baldwin et al., 2001; Pace et al., 2020). However, by presenting an animated character performing sequences of arbitrary actions devoid of visible goals, and by controlling the duration of pre-boundary lengthening and pause, we reduced the impact of top-down processing, and could therefore single out the contribution of bottom-up processing. The current study also took the novel approach of presenting infants with a combination of pre-boundary lengthening and pause. Previous studies on infant action segmentation have mainly focused on the mere insertion of a pause within or at the end of an action unit within a sequence (Baldwin et al., 2001; Meyer et al., 2011; Pace et al., 2020; Saylor et al., 2007). A pause *at the end* of an action would be expected based on both top-down cues to action conclusion following goal attainment and bottom-up cues to the termination of the goal-directed movement (e.g., deceleration resulting in pre-boundary lengthening; Zacks et al., 2009). In contrast, a pause *within* an ongoing action violates not only top-down expectations but also results in a mismatch of kinematic boundary cues, because the pause is not preceded by movement deceleration. Hence, the present study provides new evidence of infants' bottom-up processing of the kinematic boundary cues that mark boundaries in sequences of non-goal-directed actions.

Overall, our data show that kinematic boundary cues affected 12-month-old infants' processing of an action sequence. The finding of a boundary-related positivity in response to the kinematic boundary cues indicated that infants make use of these cues to segment unfamiliar action sequences already by the end of the first year of life. Given that a boundary-related positivity has also been found in response to prosodic boundary cues during the first year of life (Holzgrefe-Lang et al., 2018; Pannekamp et al., 2006; but see Männel & Friederici, 2011), the current study hints at possible shared processes underlying action and speech segmentation already at this age. In addition, the increased Nc response to the final action in the boundary condition relative to the no-boundary condition indicated that the 12-month-old infants not only detected the kinematic boundary cues, but that these cues modulated infants' processing of the subsequent action, which could support action segmentation. Further work should now begin to further disentangle the impact of conceptually-driven top-down processes and perceptually-driven bottom-up processes on action segmentation over the developmental course from infancy to adulthood.

Acknowledgements

This work was supported by a grant from the German Research Foundation (DFG, project number 258522519) within the Research Unit Crossing the Borders FOR 2253 to IW (WA 2969/7-1) and BE (EL 253/6-1). With thanks to the families who took part, Jakob Junge for help with stimuli creation, Romy Räling for help with experimental design, and the Babylab team for help with data collection.

References

Baldwin, D., Baird, J., Saylor, M., & Clark, M. (2001). Infants parse dynamic action. *Child Development*, *72*, 708-717. https://doi.org/10.1111/1467-8624.00310

Bläsing, B. E. (2014). Segmentation of dance movement: effects of expertise, visual familiarity, motor experience and music. *Frontiers in Psychology, 5,* Article 1500. https://doi.org/ 10.3389/fpsyg.2014.01500

Brand, R. J., Baldwin, D. A., & Ashburn, L. A. (2002). Evidence for 'motionese': modifications in mothers' infant-directed action. *Developmental Science*, *5*, 72-83. https://doi.org/10.1111/1467-7687.00211

Christophe, A., Gout, A., Peperkamp, S., & Morgan, J. (2003). Discovering words in the continuous speech stream: The role of prosody. *Journal of Phonetics*, *31*, 585-598. https://doi.org/10.1016/s0095-4470(03)00040-8

Church, R., Bernhardt, B., Pichora-Fuller, K., & Shi, R. (2005). Infant-directed speech: Final syllable lengthening and rate of speech. Canadian Acoustics, 33(4), 13-19. Available from: https://jcaa.caa-aca.ca/index.php/jcaa/article/view/1770

Craddock, M. (2016, November 28). ERP Visualization: Within-subject confidence intervals [Blog post]. Retrieved from https://www.mattcraddock.com/blog/2016/11/28/erp-visualization-within-subject-confidence-intervals/

de Haan, M. (2007). Visual attention and recognition memory in infancy. In M. de Haan (Ed.), *Infant EEG and event-related potentials* (pp. 101-143). New York: Psychology Press.

de Haan, M., & Nelson, C. (1997). Recognition of the mother's face by six-month-old infants: A neurobehavioral study. *Child Development*, *68*, 187-210. https://doi.org/ 10.1111/j.1467-8624.1997.tb01935.x

Floccia, C., Keren-Portnoy, T., DePaolis, R., Duffy, H., Delle Luche, C., Durrant, S., & Vihman, M. (2016). British English infants segment words only with exaggerated infant-directed speech stimuli. *Cognition*, *148*, 1-9. https://doi.org/10.1016/j.cognition.2015.12.004

Fritsch, J. N., Hofemann, N., & Rohlfing, K. (2005). Detecting ‘When to Imitate’ in a social context with a human caregiver. In: *Proceedings of the IEEE International Conference on Robotics & Automations, Workshop on The Social Mechanisms of Robot Programming by Demonstration.* Barcelona, Spain: IEEE.

Gilbert, A., Boucher, V., & Jemel, B. (2015). The perceptual chunking of speech: A demonstration using ERPs. *Brain Research*, *1603*, 101-113. https://doi.org/10.1016/j.brainres.2015.01.032

Glushko, A., Steinhauer, K., DePriest, J., & Koelsch, S. (2016). Neurophysiological correlates of musical and prosodic phrasing: shared processing mechanisms and effects of musical expertise. *PloS one*, *11*, Article e0155300. https://doi.org/ 10.1371/journal.pone.0155300

Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*(4), 468-484.

Hemeren, P. E., & Thill, S. (2010). Deriving motor primitives through action segmentation. *Frontiers in Psychology*, *1*, Article 243. https://doi.org/ 10.3389/fpsyg.2010.00243

Hespos, S., Grossman, S., & Saylor, M. (2010). Infants’ ability to parse continuous actions: Further evidence. *Neural Networks*, *23*, 1026-1032. https://doi.org/10.1016/j.neunet.2010.07.010

Hilton, M., Räling, R., Wartenburger, I., & Elsner, B. (2019). Parallels in processing boundary cues in speech and action. *Frontiers in Psychology*, *10*, Article 1566. https://doi.org/10.3389/fpsyg.2019.01566

Hockey, B. A., & Fagyal, Z. (1998). Pre-boundary lengthening: Universal or language-specific? The case of Hungarian. *Working Papers in Linguistics (University of Pennsylvania), 5*, 71-82.

Holzgrefe, J., Wellmann, C., Petrone, C., Truckenbrodt, H., Höhle, B., & Wartenburger, I. (2013). Brain response to prosodic boundary cues depends on boundary position. *Frontiers in Psychology*, *4,* Article 421. https://doi.org/ 10.3389/fpsyg.2013.00421.

Holzgrefe-Lang, J., Wellmann, C., Höhle, B., & Wartenburger, I. (2018). Infants' processing of prosodic cues: Electrophysiological evidence for boundary perception beyond pause detection. *Language and Speech*, *61*, 153-169. https://doi.org/10.1177/0023830917730590

Kaduk, K., Bakker, M., Juvrud, J., Gredebäck, G., Westermann, G., Lunn, J., & Reid, V. (2016). Semantic processing of actions at 9 months is linked to language proficiency at 9 and 18months. *Journal of Experimental Child Psychology*, *151*, 96-108. https://doi.org/10.1016/j.jecp.2016.02.003

Knösche, T., Neuhaus, C., Haueisen, J., Alter, K., Maess, B., Witte, O., & Friederici, A. (2005). Perception of phrase structure in music. *Human Brain Mapping*, *24*, 259-273. https://doi.org/10.1002/hbm.20088

Lawrence, M. A. (2016). *ez: Easy Analysis and Visualization of Factorial Experiments. R package version* 4.4-0. Available at: https://cran.r-project.org/web/packages/ez/index.html

Männel, C., & Friederici, A. (2011). Intonational phrase structure processing at different stages of syntax acquisition: ERP studies in 2-, 3-, and 6-year-old children. *Developmental Science*, *14*, 786-798. https://doi.org/10.1111/j.1467-7687.2010.01025.x

Männel, C., & Friederici, A. (2016). Neural correlates of prosodic boundary perception in German preschoolers: If pause is present, pitch can go. *Brain Research*, *1632*, 27-33. https://doi.org/10.1016/j.brainres.2015.12.009

Männel, C., Schipke, C., & Friederici, A. (2013). The role of pause as a prosodic boundary marker: Language ERP studies in German 3- and 6-year-olds. *Developmental Cognitive Neuroscience, 5,* 86-94. https://doi.org/10.1016/j.dcn.2013.01.003

Meltzoff, A.N., 1995. Understanding the intentions of others: re-enactment of intended acts by 18-month-old children. *Developmental Psychology, 31,* 838–850. http://dx.doi.org/10.1037/0012-1649.31.5.838.

Meyer, M., Baldwin, D., & Sage, K. (2011). Assessing young children's hierarchical action segmentation. In: *Proceedings of the 33rd Annual Meeting of the Cognitive Science Society, Boston.*

McAleer, P., Pollick, F. E., Love, S. A., Crabbe, F., & Zacks, J. M. (2014). The role of kinematics in cortical regions for continuous human motion perception. *Cognitive, Affective & Behavioral Neuroscience 14*, 307–318. https://doi.org/10.3758/s13415-013-0192-4

Monroy, C., Gerson, S., Domínguez-Martínez, E., Kaduk, K., Hunnius, S., & Reid, V. (2019). Sensitivity to structure in action sequences: An infant event-related potential study. *Neuropsychologia*, *126*, 92-101. https://doi.org/10.1016/j.neuropsychologia.2017.05.007

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorial in Quantitative Methods for Psychology, 4,* 61-64. https://doi.org/10.20982/tqmp.04.2.p061

Nelson, C., & Collins, P. (1991). Event-related potential and looking-time analysis of infants' responses to familiar and novel events: Implications for visual recognition memory. *Developmental Psychology*, *27*, 50-58. https://doi.org/10.1037/0012-1649.27.1.50

Pace, A., Carver, L., & Friend, M. (2013). Event-related potentials to intact and disrupted actions in children and adults. *Journal f Experimental Child Psychology*, *116*, 453-470. https://doi.org/10.1016/j.jecp.2012.10.013

Pannekamp, A., Toepel, U., Alter, K., Hahne, A., & Friederici, A. D. (2005). Prosody-driven sentence processing. An event-related brain potential study. *Journal of Cognitive Neuroscience, 17*, 407–421. https://doi.org/10.1162/0898929053279450

Pannekamp, A., Weber, C., & Friederici, A. D. (2006). Prosodic processing at the sentence level in infants. *NeuroReport*, *17*, 675–678. https://doi.org/10.1097/00001756-200604240-00024

Peters, B. (2005). Weiterführende Untersuchungen zu prosodischen Grenzen in deutscher Spontansprache [Prosodic structures in German spontaneous speech]. *AIPUK*, *35a*, 203–345. http://www.ipds.uni-kiel.de/publikationen/aipuk35a.de.html

R Core Team (2019). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/

Reynolds, G., & Richards, J. (2005). Familiarization, attention, and recognition memory in infancy: An event-related potential and cortical source localization study. *Developmental Psychology*, *41*, 598-615. https://doi.org/10.1037/0012-1649.41.4.598

Reynolds, G., & Richards, J. (2019). Infant visual attention and stimulus repetition effects on object recognition. *Child Development*, *90*, 1027-1042. https://doi.org/10.1111/cdev.12982

Richards, J., Reynolds, G., & Courage, M. (2010). The neural bases of infant attention. *Current Directions in Psychological Science*, *19*, 41-46. https://doi.org/10.1177/0963721409360003

Rohlfing, K. J., Fritsch, J., Wrede, B., & Jungmann, T. (2006). How can multimodal cues from child-directed interaction reduce learning complexity in robots? *Advanced Robotics*, *20*, 1183-1199. https://doi.org/10.1163/156855306778522532

Saylor, M., Baldwin, D., Baird, J., & LaBounty, J. (2007). Infants' on-line segmentation of dynamic human action. *Journal of Cognition and Development*, *8*, 113-128. https://doi.org/10.1080/15248370709336996

Schönebeck, M., & Elsner, B. (2019). ERPs reveal perceptual and conceptual processing in 14-month-olds' observation of complete and incomplete action end-states. *Neuropsychologia*, *126*, 102-112. https://doi.org/10.1016/j.neuropsychologia.2017.10.026

Steinhauer, K., Alter, K., & Friederici, A. D. (1999). Brain potentials indicate immediate use of prosodic cues in natural speech processing. *Nature Neuroscience*, *2*, 191–196. https://doi.org/10.1038/5757.

Thiessen, E. D., Hill, E. A., & Saffran, J. R. (2005). Infant-directed speech facilitates word segmentation. *Infancy*, *7*, 53-71. https://doi.org/10.1207/s15327078in0701_5

Twomey, K., Lush, L., Pearce, R., & Horst, J. (2014). Visual variability affects early verb learning. *British Journal of Developmental Psychology*, *32*, 359-366. https://doi.org/10.1111/bjdp.12042

Tyler, M., & Cutler, A. (2009). Cross-language differences in cue use for speech segmentation. The Journal of the Acoustical Society of America, 126, 367–376. https://doi.org/10.1121/1.3129127

Wickham, W. (2016). *ggplot2: Elegant graphics for data analysis.* New York, NY: Springer.

Zacks, J. M. (2004). Using movement and intentions to understand simple events. *Cognitive Science, 28,* 979–1008. https://doi.org/10.1207/s15516709cog2806_5.

Zacks, J. M., Kumar, S., Abrams, R. A., & Mehta, R. (2009). Using movement and intentions to understand human activity. *Cognition*, *112*, 201–216. https://doi.org/10.1016/j.cognition.2009.03.007.