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Neural processing of self-produced and externally generated events in 3-month-old infants

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A R T I C L E I N F O

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A B S T R A C T

Did I make that sound? Differentiating whether sensory events are caused by us or the environment is pivotal for our sense of agency. Adults can predict the sensory effects of their actions, which results in attenuated processing of self-produced events compared with externally generated events. Yet, little is known about whether young infants predict and discriminate self-produced events from externally produced events. Using electroencephalography (EEG), 3-month-olds' neural response to the same audiovisual stimulus was compared between a Self-produced condition and externally generated conditions with predictable timing (External–Regular) and irregular timing (External–Irregular). We hypothesized that if 3-month-olds predict self-produced events, their event-related potentials should be smallest for the Self-produced condition, strongest for the External–Irregular condition, and in between for the External–Regular condition. Cluster-based permutation tests indicated a more positive deflection (300–470 ms) for irregular stimuli compared with regular stimuli over the vertex. Contrasting the Self-produced and External–Irregular conditions showed a statistical trend within the same time window. Although not fully conclusive, this might suggest the emerging differentiation between self-produced and less predictable external events. However, there was no statistical evidence that infants differentiated self-produced events from temporally predictable external events. Our findings shed light on the emerging sense of

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agency and suggest that 3-month-olds are transitioning toward predicting and discriminating the consequences of their actions.

Introduction

The sense of agency is the sense that one's own actions cause effects in the environment. How the sense of agency develops during infancy has long fascinated developmental scientists, philosophers, and new parents alike. The sense of agency is ubiquitous during adulthood and is fundamental for becoming an intentional agent during early childhood, likely forming the basis for infants to learn from and about other intentional agents (Meltzoff, 2007). One defining element of the sense of agency is the ability to distinguish one's own actions and their effects from external events in the world (Tsakiris, Schütz-Bosbach, & Gallagher, 2007). Research with adults suggests that predicting the sensory effects of one's actions plays an important role in discriminating self-produced events from externally generated events (e.g., Blakemore, Wolpert, & Frith, 2000; Hughes, Desantis, & Waszak, 2012). As such, the phenomenon that we cannot tickle ourselves illustrates not only that we perceive self-produced effects differently from other sensory input but also that we process the sensory effects of our own actions in an attenuated fashion. This phenomenon can be explained by our precise prediction of the tactile input when trying to tickle ourselves that attenuates the tickling sensation (Blakemore et al., 2000). Thus, research with adults suggests that we discriminate our actions and self-caused effects from stimuli in the environment by predicting the sensory effects of our actions. Yet, little is known about whether early in life infants predict the sensory consequences of their actions and discriminate them from externally produced events. Whereas some behavioral evidence shows that 2- and 3-month-olds move more when their movements trigger a sensory effect (Rovee-Collier, Morrongiello, Aron, & Kupersmidt, 1978; Watanabe, Homae, & Taga, 2011; Watanabe & Taga, 2009), recent computer simulations—implemented as a "babybot"—demonstrated that the same behavioral pattern can be reproduced without any cause–effect representation (Zaadnoordijk, Otworowska, Kwisthout, & Hunnius, 2018). This calls into question to what extent young infants understand the causal relationship between their movements and corresponding effects in the environment. Through building up an internal causal model, it is possible to predict the consequences of one's actions and to discriminate self-produced stimuli from external stimuli. Adults reliably distinguish self-produced events from externally generated events, and this distinction is evident in their cortical responses (Hughes et al., 2012). To shed light on how infants distinguish their own actions and corresponding effects from external events in the world, the current study examined 3-month-olds' neural responses to self-initiated and externally initiated effects with more or less predictable timing.

In adult research, forward models are at the core of theoretical accounts of the sense of agency and the differentiation of self-produced stimuli from externally generated stimuli in particular (e.g., Decety & Sommerville, 2003; Hughes et al., 2012; Zaadnoordijk, Besold, & Hunnius, 2019). According to this notion, initiating an action leads to the prediction of its sensory consequences. By comparing the predicted sensory consequences with the actual sensory event in the environment, self-produced effects can be distinguished from externally generated effects (Haggard, Clark, & Kalogeras, 2002; Hughes et al., 2012; Tsakiris et al., 2007). The comparator model suggests that a smaller difference between expected and actual sensory events leads to an attenuated response to the event. Accordingly, the processing of self-produced sensory events is attenuated compared with that of externally generated events, which is reflected in the reduced intensity of subjective experience and the neural response to self-produced events (Hughes et al., 2012). There is converging evidence for sensory attenuation in adults coming from research using tactile events (Blakemore et al., 2000), visual events (Hughes & Waszak, 2011), and auditory events (Bäß, Horváth, Jacobsen, & Schröger, 2011; Bäß, Jacobsen, & Schröger, 2008). In the auditory domain, sensory attenuation in adults is reflected in the amplitude of the early auditory event-related potential (ERP) N1, typically elicited 100 ms after stimulation. When adults trigger a sound by pushing a button in contrast to hearing the same sound being triggered by the computer, the N1 component is reduced (e.g., Bäß et al., 2008, 2011; van Elk, Salomon, Kannape, & Blanke, 2014). As described in detail by Hughes et al. (2012), temporal predictability is likely one crucial factor underlying the reduced neural reactivity to self-produced sounds. When a sound is predicted based on temporal regularity, its actual occurrence requires less neural processing, leading to the observed attenuated response. In accord with this, externally generated sounds that are predictable in time also show a reduced N1 amplitude compared with the same sounds presented with less regular timing (e.g., Lange, 2009; Schafer & Marcus, 1973). Still, although resulting in a less pronounced difference, responses to self-produced sounds are more attenuated in adults and seem to stem from distinct neural generators compared with responses to temporally predictable sounds that are externally generated (Aliu, Houde, & Nagarajan, 2009; Korka, Schröger, & Widmann, 2019; Lange, 2011; Schafer & Marcus, 1973).

Like adults, infants are sensitive to temporal predictability in auditory stimuli (Otte et al., 2013). Already at 2 months of age, infants show a different neural response to regular and thus temporally predictable sounds compared with irregular, less predictable sounds (Otte et al., 2013). Specifically, 2-month-olds demonstrated a mismatch response (MMR) with a more positive deflection to irregular stimuli compared with the regular stimuli over frontocentral sites. However, how infants process self-produced stimuli precisely predictable in time based on their own actions remains an open question. Do infants differentiate self-produced events from temporally more and less predictable external events? In other words, would their neural response (MMR) change as a function of self-produced, temporally predictable, and temporally less predictable events?

The current study

In this study, we examined the developing sense of agency by investigating whether infants process the sensory consequences of their movements differently from externally caused events. To test whether the same audiovisual stimulus would elicit distinct brain responses in infants depending on who elicited the stimulus and how temporally predictable it was, we conducted an electroencephalography (EEG) study with 3-month-olds. The study design consisted of three within-participants conditions in which an audiovisual stimulus was *self-produced, externally generated with regular timing,* or *externally generated with irregular timing.* Making use of the differences in temporal predictability of the externally generated conditions allowed us to draw inferences on the predictability of the self-produced effects. If infants perceive the sensory consequences of their actions like adults, the current conditions should lead to a difference in infants' neural response, with self-produced events eliciting the smallest response, irregularly timed externally generated stimuli eliciting the largest response, and predictable externally generated sounds eliciting a medium-level response.

Method

Participants

We recorded EEG of 22 3-month-old infants, of whom 11 infants (10 boys) were entered in the final analysis (see "EEG data analysis" section below for details on exclusion procedure). The mean age of the infants in the final dataset was 105 days (*SD* = 9 days, range = 92–114). An additional 22 infants came into the lab but did not tolerate the EEG cap such that no EEG recording was conducted. High dropout rates in infant EEG studies are common (Stets, Stahl, & Reid, 2012) and were amplified by the young age of the current sample. Parents accompanying their infants to the testing session gave written consent for their infants' participation. Families were recruited from a database of families of mixed socioeconomic backgrounds in and close to Nijmegen, a middle-sized city in the Netherlands. All tested infants were full-term and had no indications of atypical development. Families received a children's book or 20 euros for their participation. The study was carried out according to standard guidelines and regulations approved by the regional ethics committee.

Procedure

Parents and their 3-month-old infants were invited to the EEG lab for a testing session of 1 h. On arrival, in a room adjacent to the testing room, parents were informed about the experimental procedure and infants were familiarized with the experimenter. Then, infants were fitted with an infant-sized EEG cap (actiCap, Brain Products GmbH, Gilching, Germany) in which 32 active electrodes were arranged in the standard 10–20 system. The online reference used in this setup was at electrode location FCz. For all electrodes, we aimed to get the impedances below 60 kΩ. After preparing the EEG cap, the experimenter accompanied each parent and infant to the electrically shielded testing room. The parent was seated facing a monitor screen. The infant was securely strapped into a car seat, which was placed on the parent's lap. This ensured that infants were positioned safely throughout the testing session with close proximity to their parents while minimizing any direct influence from their parents. If the infants did not tolerate the car seat, the infant was placed directly on the parent's lap. The parent was instructed to sit passively throughout the recording of about 8 min. Before starting the EEG recording, the experimenter attached a wristband with an integrated accelerometer to the infant's wrist. The side (left/right wrist) was counterbalanced across participants. For an illustration of the experimental setup, see Fig. 1. The recording session was then initiated by the experimenter from the adjacent room. The recording session contained three within-participants conditions presented in blocks: *Self-produced,* externally generated with regular timing (*External–Regular*), and externally generated with irregular timing (*External–Irregular*). In all three conditions an identical audiovisual stimulus was presented. Sound was combined with a visual stimulus based on the finding of Hyde, Jones, Porter, and Flom (2010), who showed that 3-month-olds and adults had an enhanced neural response to sound that was accompanied with visual change. The stimulus consisted of a black background with a yellow cartoon duck in the foreground that wiggled and made a trilling sound lasting for 900 ms.

Self-produced condition

In the first block, infants were presented with the Self-produced condition, in which their arm movements triggered the audiovisual stimulus. While infants were not moving, a still image of the yellow cartoon duck was presented. Once infants moved the arm with the accelerometer, their movements elicited the audiovisual stimulus. More specifically, the three-axis accelerometer measured meters per second squared. When the change in the vector of the three axes exceeded the threshold of 20, infants' movement elicited the audiovisual stimulus. For simplification, we henceforth refer to movements as only those movements that pertained to the trigger arm and elicited the stimulus. In the time during which the stimulus was presented, no further movement was registered. This block lasted for 3 min. Following the Self-produced block, the two externally generated conditions were presented in two subsequent blocks of 2-min duration each. The order of the externally generated conditions was counterbalanced across participants. In the final sample, 5 participants were presented with the External–Irregular condition and 6 participants were presented with the External–Regular condition in the second block. We chose to keep the order of the Self-produced condition constant and for it to be 3 min to maximize the chances of infants detecting the contingency between their own movements and the sensory effect (see also Bigelow & DeCoste, 2003). Although 3 min is a relatively short period of time, findings by Rovee-Collier et al. (1978) as well as Bigelow and DeCoste (2003) suggest that infants of this age can learn to associate an audiovisual effect with their movements during this period.

External–Regular condition

In the External–Regular condition, the same audiovisual stimulus as in the Self-produced condition was triggered by the computer in a fixed interval every 2000 ms (Aliu et al., 2009; Schafer & Marcus, 1973). Therefore, the occurrence of the stimulus was regular and predictable in time.

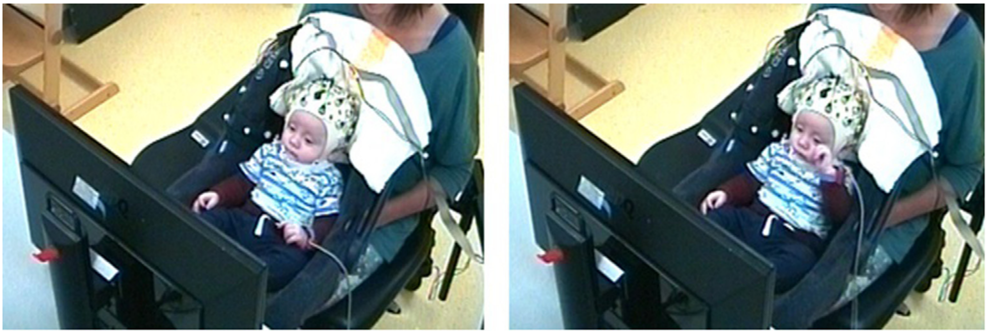

Fig. 1. The experimental electroencephalography (EEG) setup with a 3-month-old infant with an accelerometer around the left wrist. By moving the left arm, the infant triggered an audiovisual stimulus.

External–Irregular condition

The presentation of the same stimulus in the External–Irregular condition was presented automatically in a random interval ranging from 700 to 3700 ms (in steps of 200 ms). In contrast to the regular timing, the occurrence of the stimulus in this condition could not be predicted precisely in time.

Between blocks, a black screen was presented for 10 s. Throughout the testing session, infants' EEG was amplified using a BrainAmp DC EEG amplifier (Brain Products) and was digitized at 500 Hz with a bandpass filter of 0.1–125 Hz. The instances of infants' above-threshold movements were measured, and the testing session was video-recorded.

Movement data analysis

In line with previous developmental studies (e.g., Rovee-Collier et al., 1978), we assessed infants' movement behavior. In particular, we examined infants' movement frequency and the total number of times infants moved between conditions. To assess the movement frequency, we first divided each block into 10-s bins and calculated the number of movements for each bin. We then compared the median movement frequency in a repeated-measures analysis of variance (ANOVA) with condition as a factor with three levels (Self-produced, External–Regular, or External–Irregular). To compare the total number of movements between conditions, we summed up all movements per condition and entered the sum into a repeated-measures ANOVA with the same factor of condition. Because the Self-produced condition lasted 1 min longer than the other two conditions, only movements from the last 2 min in that condition were used to calculate the sum of movements. The last 2 min were chosen over the first 2 min so that infants had time to detect the action–effect contingency.

EEG data analysis

We time-locked the EEG recordings to the onset of the audiovisual stimulus for our main analysis and to the onset of infants' movements in both externally generated conditions for supplementary analyses. The data were segmented around the onset of the audiovisual stimulus with a window of 100 ms pre-stimulus/movement and 800 ms post-stimulus/movement onset. The data were bandpass filtered between 1 and 30 Hz and baseline corrected to the 100-ms pre-stimulus period. All segments were visually inspected blind to the condition, and artifacted segments were rejected from further analysis. Infants with less than 5 artifact-free trials per condition were excluded from the final analysis (n = 11). The remaining 11 infants had on average 40 trials (range = 9–108) in the Self-produced condition, 24 trials (range = 10–39) in the External–Regular condition, and 22 trials (range = 7–37) in the External–Irregular condition. The data were re-referenced to the average of all channels. To assess the ERPs dependent on condition, all trials were averaged separately for each condition. All processing of the EEG data was done using FieldTrip, an open-source MATLAB toolbox (Oostenveld, Fries, Maris, &

Schoffelen, 2011). For statistical comparisons of the time course between conditions, we used cluster-based permutation tests (Maris & Oostenveld, 2007). We focused this analysis on amplitude differences in electrode Cz. This is based on maximal differences between temporally regular and irregular sounds in awake and sleeping 2-month-olds (Otte et al., 2013) at central sites as well as research with adults showing maximal N1 effects indicating sensory attenuation over central electrodes (Hughes et al., 2012; Schafer & Marcus, 1973). Still, for transparency, all midline and adjacent electrodes are plotted in Supplementary Fig. 1 of the online supplementary material. Using a dependent-samples *t* test with the cluster-based permutation method, we first compared infants' neural response to the audiovisual stimulus presented in the two externally generated conditions (Regular vs. Irregular). This was in line with Otte et al. (2013), who reported that 2-month-olds show a more positive deflection in their neural response to a sound stimulus that has a deviating interstimulus interval compared with a regular interstimulus interval. To address our main research question on the distinction of self-produced sounds from externally generated sounds, we ran two additional contrasts with the same type of test: Self-produced versus External–Irregular and Self-produced versus External–Regular.

Results

Movement results

An illustration of the movement analysis results is provided in Fig. 2. On average, infants' median movement frequency was 4.3 movements (*SD* = 2.4) every 10 s in the Self-produced condition, 19.7 movements (*SD* = 9.4) every 10 s in the External–Regular condition, and 14.1 movements (*SD* = 8.5) every 10 s in the External–Irregular condition. Results of the repeated-measures ANOVA showed a main effect of condition, $F(2, 20) = 11.47$, $p < .001$, $\eta_p^2 = .534$. Follow-up paired-samples *t* tests yielded a significantly lower movement frequency during the Self-produced condition compared with both the External–Regular condition, $t(10) = -5.39$, $p < .001$, Cohen's $d = -1.65$, and External–Irregular condition, $t(10) = -3.83$, $p = .003$, Cohen's $d = -1.15$. This drastic increase in movement frequency is consistent with previous studies with 3-month-olds in which infants first experienced effects contingent on their movements and this contingency was discontinued in a subsequent block (e.g., Rovee-Collier et al., 1978). No significant difference was detected between the two externally generated conditions in infants' movement rate, $t(10) = 1.34$, $p = .208$, Cohen's $d = 0.40$. The same pattern of results was observed for the total number of times infants moved during the different conditions. On average, infants moved 56 times (*SD* = 27) in the Self-produced condition, 242 times (*SD* = 105) in the External–Regular condition, and 177 times (*SD* = 89) in the External–Irregular condition. A main effect of condition in the repeated-measures ANOVA, $F(2, 20) = 14.48$, $p < .001$, $\eta_p^2 = .592$, was followed up with paired-samples *t* tests, which yielded significant differences between the Self-produced condition and both externally generated conditions [Self-produced vs. External–Irregular: $t(10) = -4.68$, $p = .001$, Cohen's $d = -1.41$

Self-produced vs. External–Regular: $t(10) = -5.96$, $p < .001$, Cohen's $d = -1.79$]. Comparable to movement rate, no significant difference in the total number of movements was detected between the two externally generated conditions, $t(10) = 1.43$, $p = .18$, Cohen's $d = 0.43$. Together, both infants' movement frequency and their total number of movements were lower in the Self-produced condition than when the audiovisual effect was triggered externally.

Previous adult EEG studies on sensory attenuation typically correct the neural response to self-initiated effects with participants' neural signal during movements when they do not cause the sensory effects under investigation (cf. Bäß et al., 2008). The reason for this is to account for the lack of movement that is inherent to the externally generated conditions. In contrast to adult studies, our movement analysis shows that infants in the current study also moved in the externally generated conditions. Because there was movement in all condition types, the analyses reported below were performed without movement correction to the Self-produced ERP. For transparency, analyses with movement correction are reported in the online supplementary material.

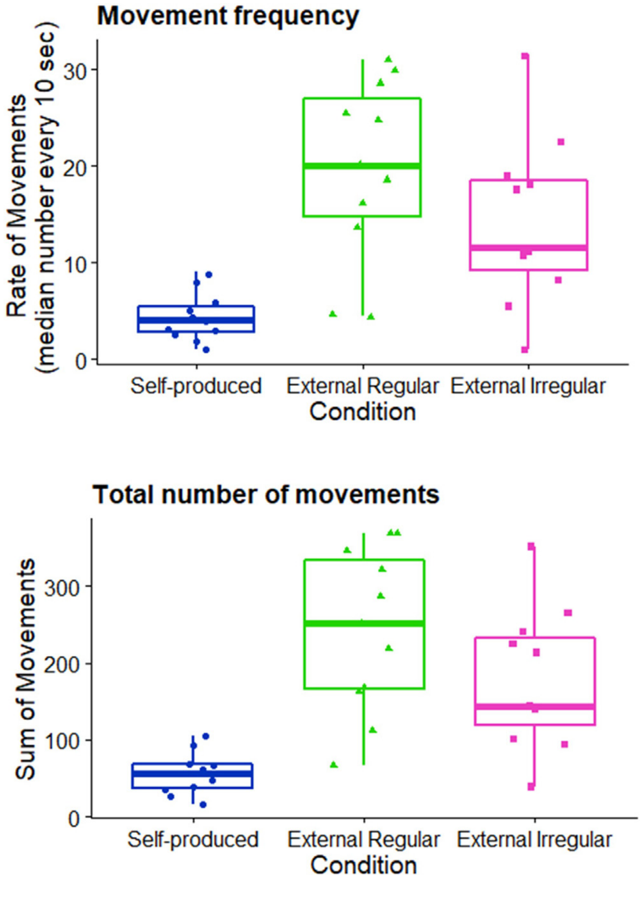

Fig. 2. Boxplots illustrating infants' rates of movement as measured by the median number of movements every 10 s (top) and their total number of movements (bottom) as a function of condition (Self-produced, External–Regular, or External–Irregular).

EEG results

External–Regular vs. External–Irregular

Contrasting infants' ERPs between the two externally generated conditions using cluster-based permutation testing yielded a significant difference ($p < .05$) between the conditions. From 292 to 472 ms, the External–Irregular condition elicited a more positive deflection in infants' ERPs compared with the External–Regular condition. The Cohen's d effect size for the average over the identified time window was 1.24, which is very large.[1] Fig. 3 (bottom left) illustrates these results. The timing and directionality of this effect are in line with previous findings by Otte et al. (2013) in 2-month-olds.

External–Irregular vs. Self-Produced

The cluster-based permutation test revealed a marginally significant difference between infants' neural response to a stimulus that was self-produced versus externally generated when the externally generated timing was irregular ($p = .06$). The Cohen's d effect size for the average over the identified time window was .91 and thus was large. This contrast between the ERPs is displayed in Fig. 3 (bottom

[1] [1]Note that effect size calculation is challenging for high-dimensional data, so it should be viewed with extra caution (see, e.g., https://www.fieldtriptoolbox.org/example/effectsize).

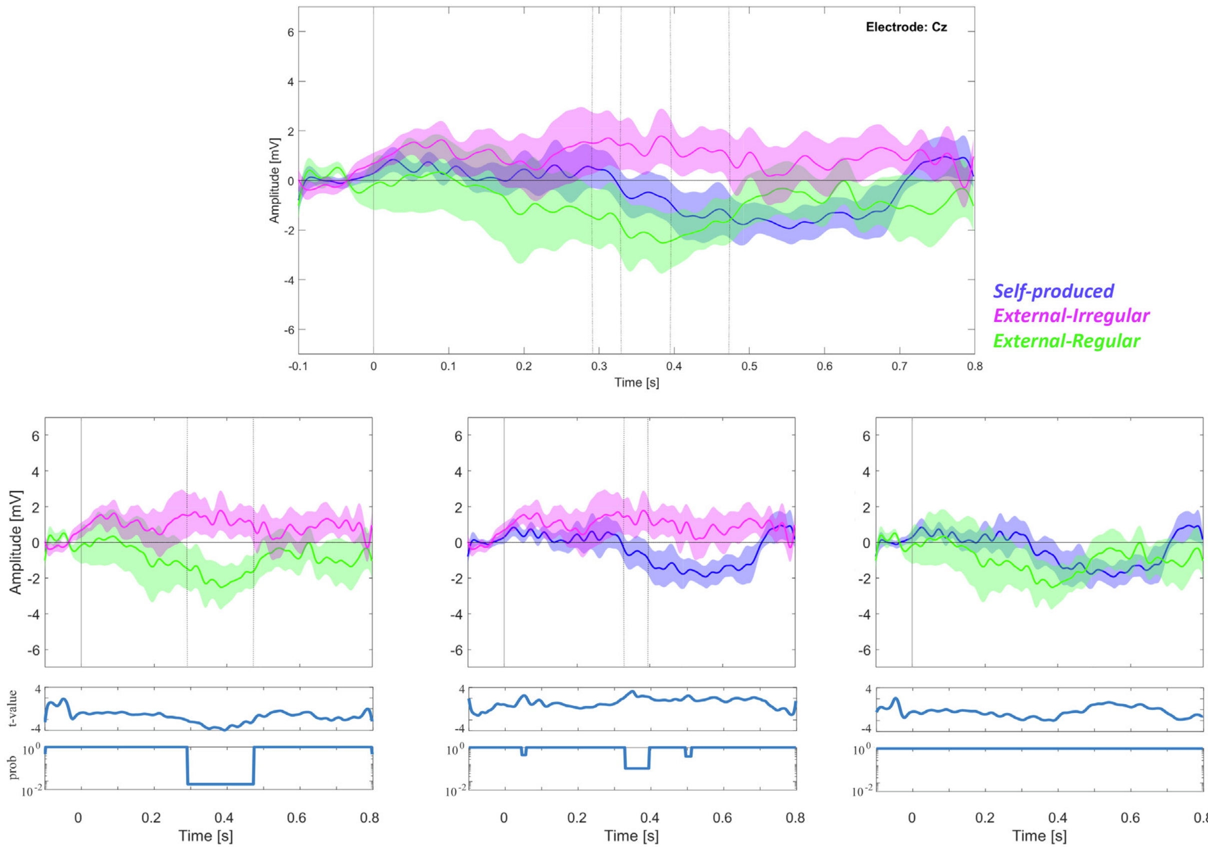

Fig. 3. Top: Infants' event-related potentials (ERPs) as a function of the three within-participants conditions: Self-produced (blue), External–Regular (green), and External–Irregular (pink). Shaded areas represent ±1 standard error around the mean (solid lines) for each condition. Bottom: infants' ERPs separated by statistical contrasts with *t* values and *p* values of the cluster-based permutation test resolved in time for each contrast below the ERPs. We contrasted External–Regular vs. External–Irregular (left), Self-produced vs. External–Irregular (middle), and Self-produced vs. External–Regular (right). Vertical gray lines indicate the time window in which the respective two conditions differ from each other. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

middle). The time window of this marginal effect (330–394 ms) falls into the time range during which the externally triggered ERPs differ depending on the predictability of their timing (regular vs. irregular).

External–Regular vs. Self-Produced

As is evident from Fig. 3 (bottom right), no significant difference was detected when comparing infants' neural response to self-produced versus externally generated sensory effects when the externally generated effects followed a predictable regular pattern ($p > .05$).

Discussion

This study examined a key aspect of young infants' developing sense of agency, namely how the infant's brain processes the sensory consequences of the infant's own actions. More specifically, we investigated whether 3-month-olds dissociate self-produced sensory events from externally generated sensory events in their neural response. For this purpose, we compared the brain response of 3-month-olds to the same audiovisual stimulus presented in three within-participants conditions: Self-produced, External–Regular, and External–Irregular. In the Self-produced condition infants' arm movements elicited the audiovisual stimulus, whereas in the other two conditions the computer triggered a temporally regular (External–Regular) or irregular (External–Irregular) presentation of the same stimulus. We hypothesized that the same externally generated stimulus would elicit distinct ERP waveforms depending on whether the stimulus is temporally regular or irregular. Based on Otte et al. (2013), we expected a stronger response for irregular externally generated stimuli than for regular externally generated stimuli. In addition, we hypothesized that infants' ERPs would differ for their self-produced stimuli compared with both externally generated stimuli by eliciting a smaller neural response if infants at this age process self-produced events like adults.

The current findings

External–Regular vs. External–Irregular

The waveforms of infants' ERPs closely resembled those reported by Otte et al. (2013), who tested similarly aged infants with auditory stimuli. In line with our hypothesis, infants were sensitive to temporal regularity in externally triggered stimuli. More specifically, we found a stronger positive deflection from approximately 300–470 ms over the vertex for infants' ERPs to temporally irregular events compared with temporally regular events. This is consistent with the findings by Otte et al. (2013) for 2-month-olds. Otte and colleagues also found a positive deflection around the same time window for irregularly timed auditory stimuli compared with regularly timed auditory stimuli over frontocentral sites.

External–Irregular vs. Self-Produced

The contrast between infants' ERPs to self-produced versus externally generated stimuli with irregular timing showed a statistical trend in the same direction. It occurred within the same time frame as the significant difference in infants' ERPs to regular versus irregular externally generated stimuli. Although this data pattern shows an interesting statistical trend, this difference does not reach significance. Therefore, we can only cautiously interpret the pattern as a first indication, rather than conclusive evidence, that 3-month-olds process self-produced effects differently from external events with irregular timing.

External–Regular vs. Self-Produced

We did not find any evidence for differences in infants' ERP responses to self-produced versus predictable externally generated sensory events. This is in contrast to what one might expect if infants processed self-produced events like adults. Also in adult studies, the difference in neural activity between self-produced and externally generated stimuli that are periodic (and thus predictable in time) tends to be substantially smaller than the difference between self-produced and temporally irregular sounds produced by the computer (Schafer & Marcus, 1973). Still, although smaller in magnitude, findings in adults show a differential neural response between self-initiated sounds and temporally predictable sounds (Aliu et al., 2009) potentially because controlling when to move and consequently when an event occurs might allow adults to perfectly predict self-initiated events. Relatedly, recent EEG research with adults has addressed whether sensory attenuation is unique to self-initiating an event or rather reflects its temporal predictability (Dogge, Hofman, Custers, & Aarts, 2019; Kaiser & Schütz-Bosbach, 2018). Results of these studies suggest that being able to predict an event might drive attenuated processing of that event. Our findings cannot speak to the question of whether predictability is more or less important for attenuation than self-production. Still, predictability is at the core of our findings and their interpretation. That is, the self-produced events become temporally predictable only when infants make the link between their movements and corresponding effects. Otherwise, self-produced events with their inherently irregular timing and the irregularly timed events of the externally generated condition (External–Irregular) should have been processed in a comparable way and differ from the regular and predictable externally generated condition (External–Regular). Therefore, as we discuss below, the statistical trend in infants' neural response to self-produced stimuli compared with externally irregularly timed stimuli may suggest that the 3-month-olds were able to predict the events based on their movements—a cornerstone in the development of the sense of agency.

Infants in transition? Insights from infants' neural response to self-produced effects

By comparing self-produced events with more and less predictable external events, the current results go beyond a binary distinction of whether or not infants perceive the sensory consequences of their actions as distinct from their environment. Both the External–Irregular and Self-produced conditions led to irregularly timed events. For participants not realizing that they are causing the events, both conditions appear to be irregularly timed and thus more similar compared with the regularly timed External–Regular condition. If, however, 3-month-olds associated their movements with the corresponding events and thus were able to predict them in time, the Self-produced and External–Regular conditions should be processed in a more similar way given that both are predictable. The statistical trend of a difference we observe between the Self-produced and External–Irregular conditions may provide interesting indications in this respect. These conditions are more alike in their variable timing compared with the periodic External–Regular condition, which follows a very precise regular timing. Although self-produced events occur rather irregularly, the neural response to self-produced events is comparable to that of predictable external events but potentially less so to irregular external events. Based on these infant findings in comparison with previous adult findings, one might speculate that infants process self-caused and environmental effects differently from adults. Previous findings suggest that to dissociate self-produced events from externally generated events, adults profit from being able to control precisely when to perform an action that then causes an effect (see Hughes et al., 2012). Infants' motor control, however, is still immature during their first months of life. Therefore, infants might not be able to rely on temporal control as much as adults do in their processing of self-produced events. Although infants might be able to generate predictions on the sensory consequences of their actions, these predictions might not be as temporally precise at this early age. That is, despite not being able to perfectly control their movements, infants still receive feedback on their movements through efference copies, which in turn might contribute to their ability to predict the self-produced sensory events. Thus, in contrast to adults, temporal control might play into the sense of agency to a lesser extent during infancy. Although this explanation remains speculative, it is in line with the current findings that illustrate similar neural activity for predictable external and self-produced events. This interpretation also allows for the generation of specific testable hypotheses for future developmental research as a function of their motor control development, infants' neural response to self-produced events should increasingly become distinct from predictable externally generated events.

Another factor that might make infants' neural processing of their self-produced effects different from that typically found in adults is an additional enhancement in attention to self-produced events. More than for adults, the contingency of an effect to one's movements might make a sensory event particularly salient for infants. Behavioral findings show, for instance, that infants pay more visual attention to socially contingent responses compared with noncontingent responses at 4 months of age (Bigelow & DeCoste, 2003). Adult research suggests that focusing attention on an event can increase, rather than reduce, the neural response to an event (see Nobre & van Ede, 2018, for a review, but see also Lange, 2009). Therefore, it is possible that the infants' ERPs to self-produced events in this study reflect a summation of signals, namely reduced processing of the self-produced events as observed in adults together with an attentional increase in processing of this stimulus resulting at an intermediate activation level. If this holds true, one might expect that attention decreases over development as infants get familiar with being able to cause sensory events in the world. Future studies are needed to test whether, across age or by manipulating attention to the sensory event, the neural signal to self-produced sensory events changes.

Another consideration is whether all infants at this early age detected the contingency between their own movements and the audiovisual event. The Self-produced condition lasted 3 min, which might not have been enough time for all infants to detect the contingency. Behavioral findings from Rovee-Collier et al. (1978) and Watanabe and Taga (2009) suggest that 3-month-olds increase their movement frequency beyond 3 min when their movements elicit a contingent effect. Still, the same findings suggest that with respect to a preceding baseline period of no effect contingency and in comparison with limbs that do not trigger an effect, 3-month-olds show increased movement frequency within the first 3 min of an effect contingency period. Moreover, other behavioral studies implementing contingency paradigms for infants of similar ages used equally short or shorter presentation times (e.g., Bigelow & DeCoste, 2003). The current behavioral distinction between self-produced and externally generated conditions suggests that infants did pick up on the contingency that constitutes the only difference between self-produced and externally generated conditions. This is in line with previous behavioral research in same-aged infants that shows differential movement rates depending on whether sensory effects are contingent on infants' movements (Rovee-Collier et al., 1978, Watanabe & Taga, 2009). Thus, although we cannot exclude the possibility that some infants did not detect the contingency, it is unlikely given previous findings and the current results.

Possible limitations

Although we observe a statistical trend suggesting that 3-month-old infants might differentiate self-produced events from less predictable external events in their neural processing, this contrast did not reach statistical significance. Thus, it remains inconclusive from these results whether or not infants at this age can reliably distinguish irregularly occurring external events from those caused by themselves. Still, this data pattern opens up interesting questions regarding the role that predictability might play in the emerging sense of agency. Thus, we proposed specific hypotheses (see above) that future research should test to shed light on the role of predictability for developing a sense of agency. The nonsignificant outcome might also be related to the relatively small number of participants in the final sample. We recorded 22 infants with EEG, but only 11 infants had sufficient artifact-free EEG trials for all three conditions. To address the current research question, we needed to study especially fragile and difficult to recruit participants using EEG methodology, which is known for leading to high dropout rates with developmental populations. Although we acknowledge this limitation, we have reason to believe that nonetheless our findings are meaningful and an important step in the study of the developing sense of agency. The significant difference between the External–Irregular and External–Regular conditions replicated previous research, and the statistical trend for the contrast of the External–Irregular and Self-produced conditions is consistent in terms of polarity and timing with this effect. That is, both contrasts show a higher amplitude for the External–Irregular condition, and this difference starts about 300 ms after stimulus onset. For the External–Irregular versus External–Regular contrast, the difference lasts for 180 ms. The statistical trend of a difference between the External–Irregular and Self-produced conditions was found for a duration of 64 ms, but it is descriptively present for a longer period (~350 ms). Subsequent studies replicating and extending these findings are important because they will offer valuable information on the reliability and robustness of the effects and potential age-related changes.

A second limitation of the current study is the semi-fixed order of conditions that always started with the Self-produced condition. This fixed order might have partly contributed to the behavioral findings because infants might have moved more at the end of the experiment. It is important to note, however, that infants' movements did not gradually increase as would be consistent with boredom, fuzziness, or fatigue effects but rather showed a jump between the first block (self-produced) and second block (externally generated). This steep increase in movement frequency is in line with previous developmental studies that first present a phase with action–effect contingency followed by a phase in which that contingency is discontinued (e.g., Rovee-Collier et al., 1978). Besides this, the order of conditions cannot explain the neural findings that show ERPs to the self-produced effect at an intermediate activation level. If the semi-fixed order had any effect, one would have expected the self-produced ERP to be at either extreme rather than falling in between the ERPs to externally generated events. The difference between the regular and irregular external events is independent of that entirely given that the order between those two conditions was counterbalanced. Thus, although the semi-fixed order might have in part influenced the behavioral findings, it does not sufficiently explain the current ERP findings.

Conclusions

Comparing infants' neural response between self-produced events and externally produced events that were less or more predictable in time allowed us to examine whether infants discriminated these events and which role predictability might play in dissociating self-produced events from externally generated events. In sum, we found no evidence that infants process temporally predictable external events differently from self-produced events. Interestingly, the statistical trend we observed between temporally less predictable and self-produced events suggests a possible difference in 3-month-olds' neural processing of self-produced and less predictable events. Because this trend did not reach statistical significance, however, it requires future studies to conclusively determine whether and which externally produced events are processed distinctly from self-produced events in 3-month-olds. Together, our findings suggest that at 3 months of age infants are still in transition toward reliably predicting and discriminating the sensory consequences of their own actions.

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Author contributions

M.M. and S.H. jointly developed the study concept and design. Both authors collected the data. M. M. performed data analyses, and both authors interpreted the data. M.M. drafted the manuscript, and S.H. contributed critical revisions. Both authors approved the final version of the manuscript for submission.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2020.105039.

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