Tracking Time in the Infant Brain

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1 Introduction

From early on, infants learn to detect, predict, and adjust to internal and external events through interaction with their environment. Research shows that aspects of timing inherent in these events seem to modulate and facilitate infants' perceptual and cognitive processing. In addition to allowing for inferences about developmental trajectories and dynamics in human ontogeny, the investigation of these timing mechanisms in infants also allows the study of the structures and functions that build the foundation of the later, mature cognitive system. That is, identifying these fundamental processes provides insight into how timing processes in adults are basically organized. Infancy research has developed a number of useful methodological approaches that made these assessments possible. In this chapter, I will review some of the most established research approaches for this very young age group. The review is also intended for researchers who are interested in the investigation of timing mechanisms early in development and who are unfamiliar with this methodology.

2 Experimental Research in Infancy

In the context of experimental research conducted with adults, experimenters can expect at least to some extent that their participants exhibit the behavior that the experiment is intended to elicit; that they are able to give relatively precise responses, such as reaction time data or verbalizations; and that they exhibit a certain level of cooperation during testing. In contrast, research methodology used with infants often relies on the monitoring of indicators that allow only indirect conclusions about the internal processes under investigation. Infancy research implies accepting the fact that usually no precise task instructions are possible; that unambiguous, overt responses cannot necessarily be expected; and that the researcher often is not able to predict to what extent infants respond to the setting and the stimuli as they are expected

to do. In other words, the variability in interpreting acquired infant data is typically high (Aslin 2007).

More than in any other age group, infants' willingness to cooperate in experimental testing and subsequent data evaluation depends on a variety of factors. First, very young children have only a short attention span (Aslin & Fiser 2005). That is, experimenters need to plan their study in a way that it allows recording data within a short period of time. Second, the content of the experimental stimuli is typically confined to material that holds at least a minimum of the infant's interest and that attracts attention to the intended place. This factor is particularly important for data collection that requires repeated presentation of the same stimuli (e.g., in event-related brain potentials designs, see below). On the other hand, the experimental stimuli should fulfill the demands of being standardized and controlled enough in order to allow for appropriate scientific inference.

Third, high levels of distractibility to both internal and external variables can generally be observed in infant populations. Therefore, visual and acoustic shielding is of particular relevance. Where not explicitly assessed, behavior is recommended to be video-recorded. Doing so guarantees that the researcher analyzes data from the experimental phases in which the infants were or were not attentive, depending on the research question. The increased distractibility also includes increased dependency in social situations, such as a caregiver's presence or absence as well as the number and experience of the experimenters. Fourth, in addition to attentional restrictions, very young children can be expected to display disproportionately high rates of random behavior, such as increased motor activity (de Haan 2007). This confounded variable may result in data contamination, data loss, high fluctuation, and high attrition rates, particularly in the context of physiological data assessment.

Fifth, following up on the finding of short attention spans, results obtained in infant experimental paradigms can be assumed to interact with infant development in other domains. For example, cognitive development early in infancy is very closely associated with social and motor development (e.g., Kopp & Lindenberger 2011, 2012). In other words, the experimental design, settings, and parameters need to take into account the respective developmental stage in several domains. Moreover, some of the experimental paradigms applied in infancy research (e.g., on perceptual processes) interact with memory. Hence, a potential confound with memory-related specificities, such as the reliability of recall and the temporal extent of memory (Bauer 2006), need to be considered in the interpretation of data thought to reflect the perceptual and cognitive processes of interest. Furthermore, overt responses in experimental

situations may interfere with premature levels of motor control and of planning and executive processes (de Haan 2007).

Sixth, in general, infant data reveal a high degree of intra- and inter-individual variability (e.g., Gilmore & Thomas 2002). This constraint is particularly significant with respect to inferential statistics. Due to high attrition rates, researchers are often required to test a large number of participants in order to identify genuine, underlying psychological mechanisms observed in reliable statistical effects.

3 Assessment of Infants' Neural Activity

Given the limitations of the interpretability of behavioral data in this young age group, it seems particularly helpful to assess physiological parameters or some other online data. In the last couple of years, neuroscience has made substantial progress in the development and application of promising methods in the infancy domain. I will discuss a few of the common questions regarding the neuroscientific approaches used with infants.

Brain undergoes considerable developmental changes both in terms of structure and function. Experimental approaches have to take such changes into account. Comparability between the mature (adult) and the immature (infant) brain activity may not always be evident. Early in ontogeny, brain maturation processes, such as synaptogenesis or the beginning of synaptic pruning, play a major role. Pronounced lifespan changes in synaptic density have been demonstrated (Huttenlocher & de Courten 1987), showing a major increase of the number of synapses after birth, while synaptic pruning is initiated a few weeks after birth and continues over the lifespan. These mechanisms are associated with progressive specialization and differentiation, both in the behavioral and the neural domain. Johnson and Munakata (2005) described the structural changes as specialization, dissociation, and structural integration. In particular, development includes processes of narrowing, increased specialization, increased localization, and enhanced focal activation. In addition to these structural changes, some empirical findings point to developmental changes in connectivity (Eiselt et al. 2001; Grieve et al. 2004; Thatcher, Walker, & Giudice, 1987). For example, according to one line of research (Thatcher 1992), changes in connectedness—indicated by changes in coherence measures of electroencephalography (EEG)—can be observed especially in the first four years of life. In the left hemisphere, sequential lengthening of intracortical connections takes place, whereas in the right hemisphere, sequential

contractions of intra-cortical connections can be observed. Furthermore, connectedness was shown to be modulated by experience-dependent variables in infants, such as motor behavior (Bell & Fox 1996) or specific cognitive capabilities (Bell & Fox 1992).

To date, EEG is one of the most widely used assessment methods for infants' neural signatures. One implication of the immaturity of brain activity early in life is the differences in scalp recordings compared to adult EEG signals. First, the functional equivalent of adult EEG frequency bands can be found in lower frequencies in small children. For example, while the frequency assigned as alpha is typically in the range of about 8–12 Hz in the adult EEG, it is in the range of about 6–9 Hz in young infants (e.g., Bell 2002; Marshall, Bar-Haim, & Fox, 2002). As a consequence, studies addressing brain's oscillatory activity have to take this issue into account. Second, developmental specificities can also be observed in event-related brain potentials (ERP). ERP components are significant deflections of neural responses time-locked to an internal or external event. Typically, they are operationalized as averaged neural discharges across a sufficient number of experimental trials. Modulations of these components are thought to reflect corresponding psychological states and processes. Infant ERP components usually differ from adult ERP components in terms of amplitude, latency, or polarity (Jing & Benasich 2006; Kushnerenko et al. 2002; Little, Thomas, & Letterman, 1999; McIsaac & Polich 1992; Wunderlich, Cone-Wesson, & Shepherd, 2006). Infant ERP data show higher inter-individual variability with respect to amplitudes and latencies (Thomas et al. 1997) and higher interference with movement artifacts or random noise. Short-term variability elicited by repeated presentation of the same or similar stimuli may be high (e.g., Thomas & Lykins 1995; Wiebe et al. 2006).

Both these and other factors require an adjustment of experimental EEG designs and parameters for infants. As for data acquisition, one has to keep in mind the overall high levels of movement artifacts, potential inattention, and fussiness resulting in high dropout rates. Moreover, for data analysis, some parameters, such as amplitude criteria for artifact control, need to be adjusted as well.

For the evaluation of experimental methodology, it is important to note that results from one source of data may dissociate from results obtained from other sources. This finding can be more pronounced than in adult research, given that adult participants may provide more precise behavioral measures than infants. In some cases, data may complement each other fruitfully. For example, de Haan and Nelson (1997) investigated infants' face perception and found ERP differences between the recognition of their mother's and a dissimilar stranger's face; however, there was no indication that the infants recognized the mother's face in the behavioral results.

4 Timing in Early Communication

Why should researchers investigate timing early in human ontogeny? The high relevance of temporal perception and action mechanisms becomes evident in the way infants learn about the world and, in particular, in the way they communicate with others. Infants learn through interaction with events in their environment, primarily from and through interaction with other people (e.g., Kopp & Lindenberger 2011, 2012). As such, perceptual and cognitive systems mature in interaction with the social communicative processes infants are engaged in. Research shows that much of the communicative content of early interaction is conveyed through the specific timing of interactive parameters (Feldman & Greenbaum 1997).

For this type of investigation, infants are usually placed in situations of free play or structured play with other people, and behavior is coded with respect to the temporal parameters of interest. Another frequently used experimental setup for the study of timing in early interaction is a double-screen setup (each individual perceives audio-visual responses of his/her interaction partner via screen). It allows the manipulation of interaction dynamics, such as social contingency or temporal contingency, while essential features of face-to-face interactions are maintained (e.g., Nadel et al. 1999).

From these investigations, we have learnt that infants learn to expect contingent responses from their environment, both in terms of content and timing, and that they are able to detect discrepancies in these interactional patterns from a very young age (e.g., Nadel et al. 1999; Striano, Henning, & Stahl, 2005, 2006). They use temporal information from an ongoing social interaction and may express the timing dynamics either in the same sensory modality (e.g., imitation; Meltzoff & Moore 1977) or internally transfer it to another sensory modality (e.g., affect attunement; Jonsson & Clinton 2006). In line with this finding, coordinated temporal interaction has been observed between infants' gazing behavior and adults' vocalization (Crown et al. 2002).

Time-series analyses of mother-infant interactions revealed that temporal coordination and synchrony play important roles in affect transfer and are related to cognitive competencies later in development (Feldman 2007; Feldman & Greenbaum 1997; Jaffe et al. 2001; Kaye & Fogel 1980). Moreover, infants' temporal interaction dynamics seem to be closely related to specific temporal patterns in the speech of their adult interaction partners (Condon & Sander 1974). Even preverbal infants engage in coordinated mutual vocalizing with adults, for example, by establishing tonal synchrony of the pitch of their utterances (van Puyvelde et al. 2015; van Puyvelde et al. 2010). On the other hand, disruptions in the temporal parameters of the reciprocal exchange between adults and infants may be associated with clinical conditions, such as depression

(e.g., Beebe et al. 2008; Field, Healy, Goldstein, & Guthertz, 1990), or with infant risk conditions (e.g., Lester, Hoffman, & Brazelton, 1985).

Why does time play such an important role in early communication? It has been repeatedly hypothesized that the tendency and the capacity to engage in interactions that are temporally coordinated with other people may be associated with biological rhythms, such as sleep-wake cyclicity or cardiac vagal tone (Feldman 2006), and that internal rhythms may be determinants of social interactions (Feldman 2007). This assumption has been corroborated by empirical findings on mother-infant synchrony obtained through dynamical systems modeling demonstrating both self-regulation dynamics and interpersonal coupling effects (Zentall, Boker, & Braingart-Rieker, 2006).

Based on their internal rhythmicity, children continuously learn to develop a sense of timing of their behavior in interaction with the timing of external events. Accumulated experience in this exchange with the environment enables them to develop their perceptual capacities and predictions about the timing, which in turn allows infants to develop and adjust their actions in the world.

5 Timing Processes as Seen through Behavioral Data

Next to the macro perspective of communication processes, researchers have been demonstrating temporal processing in infancy on a micro level. Most of this research uses observed overt infant behavior, such as eye gaze, in order to make inferences regarding the hypothesized corresponding internal states. This approach often leaves room for ambiguity and variance.

One of the most commonly applied experimental paradigms takes advantage of the phenomenon that repeated presentation of the same stimulus results in habituation to this stimulus (operationalized as decreased looking time) and the presentation of a novel stimulus in subsequent dishabituation (operationalized as increased looking time; Colombo & Mitchell 2009; Fantz 1964). The procedure may include a habituation sequence of fixed trial presentation or infant-controlled habituation (relying on the real looking time toward a stimulus). This approach is helpful in assessing the capacity of detecting differences in stimuli in preverbal infants. However, the understanding of the processes underlying habituation is a subject of debate (Sirois & Marschal 2002; Turk-Browne, Scholl, & Chun, 2008). Regarding the specific investigation of timing processes, one has to consider that the repeated presentation of stimuli in itself contains a temporal dimension.

A second behavioral approach frequently used in experimental infancy research is the inference about psychological states via the assessment of visual preference. Typically, two or more stimuli are presented simultaneously or successively, and the proportional duration of gazing toward one of the stimuli is assumed to inform the internal representation and processing of this stimulus as compared to the other stimulus/stimuli. In other words, conclusions about the internal stimulus relation are drawn from the external stimulus relation. Looking times are usually compared against chance level. The procedure may include a familiarization phase to a specific stimulus, after which novel stimuli are introduced for comparison; otherwise, infants utilize their experience and knowledge without a specific familiarization phase.

Experimental approaches using infant gaze as the dependent variables are subject to a number of limitations. For example, the validity and reliability of the results and the conclusions that can be drawn may be challenged (see factors influencing infant data evaluation described above). Moreover, the question is how comparable different looking times really are, for example, with respect to different age groups or the possible confound of memory interference effects (Houston-Price & Nakai 2004). Furthermore, the interpretability of results in the absence of a statistically reliable effect or the evaluation of familiarity versus novelty preference are debatable (for detailed discussions, see Aslin 2007; Aslin & Fiser 2005). Nevertheless, statistically significant results may provide reliable indicators of internal mental states, particularly detection and discrimination capabilities.

These behavioral approaches have been used to study infants' cognitive capacities to perceive temporal patterns and relations. Sensitivity to temporal phenomena, such as tempo, duration, rhythm, velocity, or synchrony between sensory modalities in multisensory events, has been demonstrated at early ages (Bahrick 2001; Byrne & Horowitz 1984; Dannemiller & Freedland 1989; Lewkowicz, Leo, & Simion, 2010; Pickens & Bahrick 1997; Spelke 1979). These capacities undergo developmental changes in terms of precision and complexity during the first months and years of life (Bahrick 2001; Bahrick & Lickliter 2004; Lewkowicz 2000a; Pickens et al. 1994). Infants' capacity to perceive intersensory synchrony, which is assumed to precede responsiveness to duration, rate, and rhythm (Lewkowicz 2000b), seems to be of particular relevance to their early experience of learning about and interacting with the world. In other words, being able to relate two sensory stimulus components as belonging to each other based on their temporal coincidence helps infants to extract and ascribe meaning to the world around them. Very young infants can already detect asynchrony between audition and vision in audiovisual

stimuli (Bahrick 1983; Dodd 1979; Lewkowicz 1996, 2010). Furthermore, young children use synchrony between auditory and visual stimuli for rhythm discrimination (Bahrick & Lickliter 2000), affect discrimination (Flom & Bahrick 2007), speech processing (Hollich, Newman, & Jusczyk, 2005), and word learning (Jesse and Johnson 2016). Perceptual experience of audiovisual synchrony relations and active experience with the timing of audiovisual events (e.g., drumming experience) may, in turn, increase infants' sensitivity to discern between audiovisual synchrony and asynchrony (Gerson et al. 2015; Pons et al. 2012).

6 Eye Movements

Global eye gaze data can provide empirical evidence to a number of research questions. In the domain of timing processes, however, it may be useful to rely on measures and paradigms that allow for the possibility of tracking temporal dynamics. Based on the idea that looking behavior may suggest what is in an infant's mind, internal timing dynamics can be made visible with higher precision and validity.

Eye tracking has been increasingly used in infant populations. The availability and application of this method have improved substantially, allowing for the assessment of precise spatial and temporal information regarding infants' eye gaze (e.g., Aslin & McMurray 2004; Gredebäck, Johnson, & von Hofsten, 2010).

These experimental techniques increase the possible spectrum of insight into psychological processes in infants and allow for inferences about temporal aspects of selective attention (Lewkowicz & Hansen-Tift 2012), action perception (Van Elk et al. 2008), categorization (McMurray & Aslin 2004), scanning dynamics (Hunnius & Geuze 2004), attentional disengagement (Hunnius, Geuze, & van Geert, 2006), anticipatory processes (Hunnius & Bekkering 2010; McMurray & Aslin 2004), predictive changes (such as the representation of temporarily occluded objects; Gredebäck & von Hofsten, 2004), integration of audiovisual speech information (Guiraud et al. 2012), the role of audiovisual temporal synchrony in infants' attention to a talker's face (Hillairet de Boisferon et al. 2016), and the timing of responses to multisensory stimuli as compared to unisensory stimuli (Neil et al. 2006).

For example, to assess specific aspects of social interactions, such as speech perception, it may be helpful to gain information about infants' precise gaze direction. It is known that, in the second half of the first year of life, infants shift their attention from a talker's eyes to a talker's mouth suggesting

a developmental shift in the use of available speaker information. Using eye-tracking methodology, Hillairet de Boisferon et al. (2016) were able to demonstrate developmental differences of attentional indicators of the direction and the duration of infant gaze as a function of audio-visual speech coherence. Thus, high spatial and temporal resolution allow for greater insight into the dynamics of social and cognitive development.

7 Neural Dynamics

Neurophysiological data may also provide insight into infants' internal states relatively independent of the child's overt behavior. In many cases, neurophysiology complements behavioral observation. While some neurophysiological imaging techniques, such as near-infrared spectroscopy (NIRS) and magnetic resonance imaging (MRI), are increasingly used in the infancy domain (e.g., Aslin & Mehler 2005; De Vita et al. 2006; Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Emberson, Richards, & Aslin, 2015; Prastawa, Gilmore, Lin, & Gerig, 2005), other techniques, such as EEG, are already well established. EEG measures allow monitoring of neural activity with high temporal resolution, which makes them a preferred method for investigating timing dynamics in the very young brain. Typically, neural activity is studied as recorded in either a continuous state or behavior, such as rest or play, or time-locked to a specific external or internal event. As discussed above, the human EEG undergoes pronounced developmental changes (e.g., Picton & Taylor 2007) and thus the interpretation of EEG data elicited as responses to an experimental manipulation has to consider these changes.

Oscillatory activity in neural signals provides information about temporal fluctuations in the frequency domain of the EEG. Spectral analysis has been successfully used for several years in the investigation of spontaneous EEG (e.g., Bell & Fox 1992, 1996). However, the acquisition of infants' time-locked oscillatory responses to experimental stimulus manipulation is still a sparse field of research. Here, due to the specificities of the infant EEG (see above), some methodological questions are not yet sufficiently resolved. Furthermore, the correlation of neural activity in certain frequency bands to perceptual or cognitive states and processes is often not as clear as it is in comparable adult research. Yet, initial studies have provided promising findings regarding the temporal processing in the infant brain. Of particular interest have been infants' neural responses to action observation processes.

Differences in event-related synchronization of alpha/mu band activity were observed in infants' observation of ongoing goal-directed versus

non-goal-directed movements (Nyström et al. 2010) and in observation versus execution of goal-directed action (Marshall, Young, & Meltzoff, 2011). Moreover, temporal neural dynamics associated with the observation of movements were significantly related to the infants' own motor experience (van Elk et al. 2008). Analysis of oscillatory activity also has the potential to provide information about the time function of internal states during the processing of ongoing actions. For example, alpha band activity was found to be attenuated not only during the observation of a grasping action, but also prior to the event when the stimulus allowed for anticipation of the occurrence of this action (Southgate, Johnson, Osborne, & Csibra, 2009). When actions are temporally occluded and the timing of movements is manipulated through introduction of continuous versus non-continuous movement, EEG signatures showed that attention- and memory-related processes (revealed in alpha and theta oscillations) support infants' tracking and internally representing observed movement (Bache et al. 2015).

A more widely established measure in infancy research is event-related brain potentials (ERP, see above). One experimental procedure that has produced a large body of literature is the measurement of the mismatch negativity (MMN), an ERP component elicited and modulated by deviant acoustic stimuli in a continuous stream of homogeneous stimuli (e.g., Cheour 2006; Jing & Benasich 2006). A major advantage of the MMN is that it can be assessed already at the beginning of life and also while infants are asleep (Cheour et al., 2002a; Cheour et al., 2002b). MMN modulations reflect preattentive processing and can be regarded as stable and reliable indicators of the temporal dynamics of auditory sensory memory. Using MMN assessments, very early neural responsiveness to several dimensions of timing were revealed, including stimulus duration (e.g., Cheour et al., 2002a, 2002b), interval timing (Brannon et al. 2004), ratio of occurrence of different inter-stimulus intervals (Brannon et al. 2008), temporal resolution operationalized as gap detection thresholds (Trainor et al. 2001), and variations in the frequency spectrum of sounds (Kushnerenko et al. 2007), among others.

Apart from mismatch responses, ERP correlates of temporal processing in infants were identified both for unisensory (e.g., Kushnerenko et al. 2001; Purhonen et al. 2005; Rosander et al. 2007) and multisensory stimuli. As described earlier, infants rely preferably on temporal coincidence of sensory information to make sense of the world around them. Hence, the study of infants' capacities to bind information from two sensory modalities together, such as audition and vision, has received increased interest. Using ERP, early processing differences were shown for congruence versus incongruence of

concurrently presented auditory and visual information (Bristow et al. 2008). Moreover, in line with findings in the adult brain, in very young infants visual stimuli modulate auditory ERP responses when presented simultaneously with acoustic stimuli (Hyde et al. 2010). ERP modulations were also observed in response to asynchronous versus synchronous presentation of a static face and of speech sounds as well as in response to congruence versus incongruence of dynamic visual and auditory speech streams (Hyde et al. 2011).

Neural correlates of audiovisual synchrony relations—independent of identity, congruence, or static versus dynamic presentation—were examined in two studies using non-speech stimuli (Kopp 2014; Kopp & Dietrich 2013). Infants saw and heard a person clapping her hands at a fixed time interval. In an infant-controlled habituation paradigm, they did not detect a temporal discrepancy of 200 ms between audition and vision behaviorally (Kopp 2014), but showed dishabituation to a 400-ms asynchrony (Kopp & Dietrich 2013). In contrast, neural activity differentiated not only between synchrony and asynchrony (400 ms) perception, but also between synchrony and the subliminal temporal discrepancy (200 ms). Although the experimental manipulation included a temporal shift only in the visual modality, auditory ERP activity was significantly modulated relative to the synchrony conditions in both experiments. Moreover, results demonstrated that infants predictively adjusted their ongoing neural activity very early after stimulus onset, resulting in an asynchronous (400 ms) or temporally fused (200 ms) multisensory percept, respectively. In other words, depending on temporal synchrony relations between vision and audition and on how they were perceived behaviorally, brain signatures showed significantly different activity modulations that followed expectancy processes.

These two latter studies are examples of the potential of the assessment of online physiological measures and of the usefulness of collecting complementary measures (in this case, behavior and EEG) in the infancy domain. The overview in this chapter has demonstrated that the investigation of timing and temporal perception early in human development is still a developing research area. Some progress has been made both in the development of appropriate experimental methodology in infancy and in the understanding of timing mechanisms. Timing plays an important role both on a macro level, as seen in social interactions, and on a micro level, as observed in individual perceptual and cognitive processes. It seems fair to assume that research methods providing fine-tuned, online behavioral, and physiological measures are increasingly used. They make it possible to address the correlation between infants' psychological states and the processing characteristics of internal and external events

in high temporal resolution, which is particularly useful in the field of timing phenomena. For present and future research, the combination of expertise in infancy research, neuroscience, cognitive psychology, and other related disciplines seems the most promising in terms of increasing insight into this fascinating field of research.

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