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Detecting violations of temporal regularities in waking and sleeping two-month-old infants

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ABSTRACT

Correctly processing rapid sequences of sounds is essential for developmental milestones, such as language acquisition. We investigated the sensitivity of two-month-old infants to violations of a temporal regularity, by recording event-related brain potentials (ERPs) in an auditory oddball paradigm from 36 waking and 40 sleeping infants. Standard tones were presented at a regular 300 ms inter-stimulus interval (ISI). One deviant, otherwise identical to the standard, was preceded by a 100 ms ISI. Two other deviants, presented with the standard ISI, differed from the standard in their spectral makeup. We found significant differences between ERP responses elicited by the standard and each of the deviant sounds. The results suggest that the ability to extract both temporal and spectral regularities from a sound sequence is already functional within the first few months of life. The scalp distribution of all three deviant-stimulus responses was influenced by the infants' state of alertness.

1. Introduction

The perception and representation of timing in the human brain has been fascinating researchers for a long time. Temporal processes have been separated into different time scales from circadian rhythms to processes in the millisecond range (Mauk and Buonomano, 2004) and numerous studies were carried out to gain insight into mechanisms underlying temporal processing in the brain (e.g. Mauk and Buonomano, 2004; Ivry and Spencer, 2004; Lewis and Miall, 2009; Koch et al., 2009). Most studies into the subject have been conducted on adults and pre-school and school-age children. Less is known, however, about the temporal processing abilities of infants. Extending our knowledge about these processes is fundamental for understanding developmental milestones, such as language acquisition, in which temporal processes play an important role. For example, in some languages phoneme duration may distinguish between minimal pairs of words (Peterson and Lehiste, 1960). Also, several studies showed that the ability to accurately process the temporal characteristics of rapidly presented sequences of sounds is critical for analysing and segmenting spoken language (Tallal et al., 1985; Benasich and Leevers, 2002; Fitch et al., 2001; Benasich et al., 2006). Therefore, the aim of the current study was to test whether infants are sensitive to violations of temporal regularities, i.e. to unpredictable changes in the timing of auditory stimulus delivery.

Using cardiac responses and behavioural measures, it has been shown that infants are sensitive to some temporal stimulus parameters and have a degree of control over timing their actions. For example, Pouthas et al. (1996) found that newborns and two-month-olds could learn to time pauses between non-nutritive sucks. Jusczyk et al. (1983) and Eilers et al. (1984) obtained evidence showing that two-month-old infants accurately discriminated sounds that differed by a few hundred milliseconds in duration. In five-month-old infants, Chang and Trehub (1977) demonstrated discrimination between multi-tone patterns of identical tonal components but different temporal arrangements of the tones.

Studies using electrophysiological methods have also provided insights into stimulus processing in infants. A number of these studies measured infant analogues (Alho et al., 1990) of the mismatch negativity (MMN; Näätänen et al., 1978) event-related brain potential (ERP). The MMN is a cortical response to deviations from the regular features of a sound sequence (for a recent review, see Näätänen et al., 2011) and it has been suggested to reflect

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processes evoked by failed auditory predictions (Winkler, 2007). The MMN is most often studied in the auditory oddball paradigm, in which a repeating sound is occasionally exchanged for a different sound. However, violations of complex regularities can also evoke the MMN (Näätänen et al., 2001).

The MMN component has been extensively studied in adults. Relevant for the current study are the MMN results regarding the detection of violations of temporal regularities. The MMN has been elicited by occasional decreases and increases in stimulus duration (Näätänen et al., 1989; Winkler et al., 1996), shortenings of the stimulus onset asynchrony (SOA; onset-to-onset interval) and the inter-stimulus interval (ISI; offset-to-onset interval; Nordby et al., 1988; Takegata et al., 2001), stimulus omissions (Yabe et al., 1997), and infrequent changes in the temporal structure of complex sounds (Grimm and Schröger, 2005; Winkler et al., 1998) and sound patterns (Müller and Schröger, 2007; Takegata et al., 2005; Winkler and Schröger, 1995). These studies provided evidence that the various temporal aspects of auditory stimulation are encoded in the memory underlying the MMN response and that the MMN is elicited by violations of temporal expectations (for a review, see Czigler et al., 2003).

MMN experiments are quite suitable for infant studies, because, in contrast to most other ERP components, MMN-like discriminative ERP responses ('mismatch responses'; MMRs) can be obtained very early in infancy (Cheour, 2007), they require no behavioural response (Nelson and Bloom, 1997), and are elicited by unattended stimuli also (Sussman, 2007). Furthermore, the component can be recorded in waking as well as in sleeping infants (Kushnerenko et al., 2001a), although mixed results have been found as to whether or not the infant's state of alertness influences the MMR (see for example Friederici et al., 2002; Hirasawa et al., 2002; Cheour et al., 1998).

Despite the advantages, only a relatively small number of MMN experiments tested violations of temporal regularities in infants. Kushnerenko et al. (2001b) showed that infants aged 2–6 days are sensitive to increases in tone duration, evident in changes in their N2 responses. Also, Kushnerenko et al. (2001a) found that neonates are able to discriminate duration changes in speech sounds, demonstrated by a negative inflection in their ERP wave. Winkler et al. (2009b) obtained an MMR to violations at the downbeat of a rhythmic sound pattern in newborn infants. Finally, results from an experiment by Brannon et al. (2004) suggested that ten-month-old infants could accurately detect changes of a temporal interval within a sequence of tones.

These studies showed that infants and even neonates have some sense of timing and they react to temporal deviations with a discriminative response comparable to the adult MMN. The goal of the current study was to shed light on whether infants can identify violations of temporal regularities in a repetitive auditory sound sequence, by testing whether they detect occasional shortenings of the otherwise uniform ISI. In addition, since some studies suggested that the MMR may vary as a function of the infant's state of alertness (Friederici et al., 2002) and approximately half of the infants were asleep during the EEG recording, the effects of the state of alertness on the MMR were examined by comparing the ERP responses between waking and sleeping infants. The stimulus paradigm, developed for our ongoing longitudinal study, was adapted from the one designed by Kushnerenko et al. (2007), adding ISI deviants to the rare environmental (contextually novel) and white noise sounds (high spectral deviance) embedded in a regular sequence of a repetitive complex tone. The effects of the infants' state of alertness on the responses to the rare environmental and white noise sounds will also be presented.

2. Methods

2.1. Subjects

Subjects were 76 infants whose mothers have been taking part in a longitudinal study on prenatal early life stress (PELS project). The study was approved by the Medical Ethical Committee of St. Elisabeth Hospital in Tilburg, The Netherlands. Informed consent was obtained from all mothers and fathers in accordance with the Declaration of Helsinki.

For the PELS project, a total of 190 pregnant women had been recruited, of whom 178 before their 15th and 12 between their 15th and 23rd week of pregnancy. Recruitment took place at a general hospital and four midwives' practices in and around Tilburg, The Netherlands. Pregnancies were dated using crown-rump length (CRL) around the 12th week of pregnancy measured by a professional, or the last menstrual period when CRL data were unavailable. The women were followed up during their pregnancies and were invited for postnatal observations either two or four months after the birth of their babies. Ninety-one women visited the lab for testing when their babies (54 girls) were aged two months and of these recordings, data from 76 infants (46 girls) were suitable for analysis. Data from 15 infants were excluded from the analyses due to crying (2), excessive movements/artifacts (9), and technical problems (4). The mean age of the remaining infants at testing was 9.6 weeks (M = 70.1 days, SD = 6.2 days). Mean gestational age and mean birth weight were 39.9 weeks (SD = 10.5 days) and 3454 g (SD = 474 g), respectively. All infants were healthy and had passed a screening test for hearing impairments, performed by a nurse from the infant health care clinic, between the 4th and 7th day after birth. During testing in our lab 36 of the infants were awake (20 girls) and 40 were asleep (26 girls).

2.2. Stimuli

The stimulus sequences consisted of 4 types of tones – one standard and three deviants – each with 10 ms rise and fall times and of 200 ms duration. Stimuli had an intensity level of 75 dB and were delivered at a uniform 300 ms ISI (offset-to-onset), except for the ISI-deviant events (see below). The standard sound was presented at a probability of .7 and the three types of deviants with a probability of .1, each. The standard was a complex tone constructed from the 3 lowest partials. The fundamental frequency was 500 Hz and the intensity of the second and third partials was 6 and 12 dB lower, respectively, than that of the first one. One deviant was identical to the standard sound, but preceded by 100 ms instead of 300 ms ISI ('ISI-deviant'). The other two deviant types (spectral deviants) were white noise segments ('white noise sound') and environmental sounds ('novel sounds', 150 different ones), such as a barking dog and a doorbell. Each novel sound was delivered only once during the experiment to maintain novelty throughout.

Sounds were presented in a semi-random order with the restriction that both white noise and novel sounds were always preceded by at least two standard sounds or a combination of a standard sound and an ISI-deviant. Also, consecutive ISI-deviants were always separated from each other by at least two standards or by a standard combined with either a white noise or novel sound. In total, 1150 standard sounds were presented and 150 deviants of each type. The stimuli were divided into five blocks of 300 stimuli, each and presented with short breaks in between. The order within the five stimulus blocks was separately randomised, and their presentation order was counterbalanced across subjects.

2.3. Procedure

The infants were tested at the developmental psychology lab at Tilburg University, The Netherlands, in a dimly lit and sound-attenuated room. During the experiment, parents were seated in a chair facing a pair of speakers whilst holding the infant in their arms. The speakers were placed 60 cm apart, both ca. 80 cm from the baby's head. The parent-child dyad was observed through a pair of cameras and notes were taken on whether the baby was quiet, crying, awake or asleep and whether or not he/she was sucking a pacifier, the parent's finger, a toy, etc. As some authors (e.g. Friederici et al., 2002) found that in infants the MMRs to deviant sounds changed as a function of the state of alertness, we divided our sample into a waking and a sleeping subgroup and state of alertness was later used as a between-subjects factor in the analyses. The monitored behaviour in combination with the online electroencephalography (EEG) signal was used to determine in which state of alertness the baby was during each stimulus block: awake or asleep with active (REM) and quiet (non-REM) sleep collapsed into a single category. Only data recorded during those stimulus blocks in which the infant was either awake or asleep throughout the whole period were analysed.

Before the start of the experiment, the infants were familiarised with the standard sound, the ISI-deviant and the white noise segments. The novel sounds were not included in this pre-test making sure that they were indeed new to the infants during the actual experiment. The standard sound thus became a 'frequent familiar' stimulus, the white noise sound and the ISI-deviant 'infrequent familiar' and the novel sounds 'infrequent unfamiliar' stimuli (Richards, 2003).