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The integration of audio – tactile information is modulated by multimodal social interaction with physical contact in infancy

Yukari Tanaka[a,*], Yasuhiro Kanakogi[b,c], Masahiro Kawasaki[d,e], Masako Myowa[a]

[a] Graduate school of Education, Kyoto University, Kyoto, Japan
[b] NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, 2-4 Hikaridai, Seika-cho, Souraku-gun, Kyoto 619-0237, Japan
[c] Japan Society for Promotion Science, Kojimachi Business Center Building, 5-3-1 Kojimachi, Chiyoda-ku, Tokyo 102-0083, Japan
[d] Rhythm-based Brain Information Processing Unit, RIKEN BSI-TOYOTA Collaboration Center, Saitama, Japan
[e] Department of Intelligent Interaction Technology, Graduate School of Systems and Information Engineering, University of Tsukuba, Ibaraki, Japan

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ABSTRACT

Interaction between caregivers and infants is multimodal in nature. To react interactively and smoothly to such multimodal signals, infants must integrate all these signals. However, few empirical infant studies have investigated how multimodal social interaction with physical contact facilitates multimodal integration, especially regarding audio − tactile (A-T) information. By using electroencephalogram (EEG) and event-related potentials (ERPs), the present study investigated how neural processing involved in A-T integration is modulated by tactile interaction. Seven- to 8-months-old infants heard one pseudoword both whilst being tickled (multimodal 'A-T' condition), and not being tickled (unimodal 'A' condition). Thereafter, their EEG was measured during the perception of the same words. Compared to the A condition, the A-T condition resulted in enhanced ERPs and higher beta-band activity within the left temporal regions, indicating neural processing of A-T integration. Additionally, theta-band activity within the middle frontal region was enhanced, which may reflect enhanced attention to social information. Furthermore, differential ERPs correlated with the degree of engagement in the tickling interaction. We provide neural evidence that the integration of A-T information in infants' brains is facilitated through tactile interaction with others. Such plastic changes in neural processing may promote harmonious social interaction and effective learning in infancy.

1. Introduction

Infants learn social behaviors through interaction with others. Such interaction involves sensory information, which is multimodal in nature. Infants may simultaneously receive visual (smiles, and eye contact), auditory (infant-directed speech) and tactile (gentle touches) information (Sullivan and Horowitz, 1983; Nishimura, Kanakogi, & Myowa-Yamakoshi, 2016). To react interactively and easily to such multimodal input, infants have to integrate all these signals. The mechanisms by which infants integrate audio − visual (i.e., A-V) (Bahrick, Netto, & Hernandez-Reif, 1998; Lewkowicz and Ghazanfar, 2009; Lewkowicz, 2010) and visual − tactile (i.e., V-T) information (Zmyj, Jank, Schütz-Bosbach, & Daum, 2011; Bremner, Holmes, & Spence, 2008) are increasingly understood. However, relatively little is known about the developmental mechanism involved in the integration of A-T information, and its function.

The integration of A-T information should particularly be understood during social interactions, given the role of tactile and speech signals in the context of affective bonds between caregivers and infants. Coupled A-T cues help to regulate infants' emotional state and attention, which encourages harmonious interaction between mothers and infants (Jahromi, Putnam, & Stifter, 2004). Young infants are also sensitive to such A-T stimulation in natural communicative situations; 4 − 6-month-old infants often laugh in response to A-T tickling stimulation (Sroufe and Wunsch, 1972; Sroufe and Waters, 1976). During tickling interactions, caregivers often say "tickle" using infant-directed speech, or they show their hands to the infants (Fogel, Nelson-Goens, Hsu, & Shapiro, 2000; Messinger, Dickson, & Fogel, 2001; Negayama and Yamaguchi, 2005). These multimodal signals facilitate the integration of arbitrary multimodal information (Slater, Quinn, Brown, & Hayes, 1999; Hernandez-Reif and Bahrick, 2001), emphasizing significant features within the environment (Gogate, Bahrick, & Watson, 2000; Gogate, Walker-Andrews, & Bahrick, 2001). Thus, infants may integrate auditory and tactile information through social interactions.

Yet, it remains unclear how A-T information is integrated in infants' brains through the experience of tactile interaction. Only 1

* Corresponding author at: Graduate School of Education, Kyoto University Yoshida – Honmachi, Sakyo – Ku, Kyoto 606 – 8501, Japan.
E-mail address: tanaka.yukari.62x@st.kyoto-u.ac.jp (Y. Tanaka).

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electroencephalogram (EEG) study has investigated whether young children integrate A-T information (i.e., pure tone and vibration) (Russo, Foxe, Brandwein, Altschuler, Gomes et al., 2010). The study showed stronger event-related potentials (ERPs) around 100 − 200 msec at temporal and central sites when children perceived multimodal A-T stimuli, as compared to unimodal stimuli. However, the previous study did not focus on the effects obtained in the context of social interaction. If infants integrate A-T information in a social situation, their neural processing involved in A-T information would be modulated. ERPs can describe the time course of neural processing in infants' brains, which reflects stimulus processing at different functional stages during integration of A-V (Kushnerenko, Teinonen, Vikein, & Csibra, 2008; Grossman, Striano, & Friederici, 2006) and V-T (Rigato, Begum Ali, van Velzen & Bremner, 2014) information. Furthermore, the activity of specific frequency ranges, such as beta (about 15 − 20 Hz) and gamma (above 40 Hz) bands, is related to the integration of multimodal information (Asano, Imai, Kita, Kitajo, Okada, et al., 2015; Schneider, Lorenz, Senkowski, & Engel, 2011). Thus, by using EEG and ERPs, the dynamic neural processing involved in A-T integration modulated by social interaction can be assessed.

As mentioned above, tickling interactions facilitate investigation of A-T integration. In typical tickling interactions between adults and infants, there are synchronized multimodal cues that encourage infants to integrate A-T information. Our pilot study showed that, during natural mother − infant tickling interactions, infants show anticipatory coordinated behaviors, depending on the A-T cues provided by their mothers. Initially, mothers often spoke to and simultaneously tickled the infants, who laughed reactively; after several interactions, mothers spoke before they tickled the infants, who exhibited anticipatory body movement prior to tickling (see Supplementary Information). To reveal the plastic changes facilitating A-T integration, we focused on the perception of auditory information modulated by the experience of multimodal tickling interaction. The omission paradigm allows assessment of whether unimodal information processing is modulated by multimodal experiences, by evaluating how multimodal stimuli are associated in the brain (den Ouden, Friston, Daw, McIntosh, & Stephan, 2009; Emberson, Richards, & Aslin 2015). It involves (i) simultaneous presentation of 2 or more stimuli from different modalities, to allow infants to associate them, before (ii) recording the neural responses to perception of only 1 of these stimuli (when they are no longer paired).

The present study investigated how neural processing of A-T integration is modulated by multimodal social interaction involving physical contact during infancy. We focused on 7 − 8-month-old infants, as their brains have shown evidence of integration of multimodal information (Kushnerenko et al., 2008; Grossmann et al., 2006; Rigato et al., 2014). We used the omission paradigm in 2 phases: the exposure and the test phases. During the exposure phase, infants heard one pseudoword while being tickled (multimodal 'A-T' condition) and another while not being tickled (unimodal 'A' condition). In the test phase, we used EEG to measure the infants' brain activity when they heard the same pseudowords in the absence of tickling. We compared the ERPs and oscillatory responses between these conditions. We considered 2 hypotheses. First, we predicted that A-T information is integrated through the tickling interaction, which will be reflected as stronger ERPs in the early period (before 200 msec after stimulus onset) and higher beta- or gamma-band activity at temporal and central sites for the A-T compared to the A condition (Russo et al., 2010). Second, we predicted that, as a result of integrating A-T information, expectation-related somatosensory responses will be elicited for the A-T condition compared to the A condition. The neural response to an omitted stimulus is measured using a negative component, the N250 (occurring 250–450 msec from stimulus onset) (Garrido et al., 2009), as reported in somatosensory systems (Kekoni, Hämäläinen, Saarinen, Gröhn, Reinikainen, Lehtokoski et al., 1997; Akatsuka, Wasaka, Nakata, Inui, Hoshiyama, & Kakigi, 2005). Oscillatory responses in the theta-range in infancy reflect expectation of upcoming stimuli (Stroganova, Orekhova, & Posikera, 1998; Orekhova, Stroganova, & Posikera, 1999). A stronger N250-like response and higher theta activation should be obtained when somatosensory systems respond to omitted, but expected, stimuli as a result of A-T integration. We also investigated whether ERP responses are related to infants' behavior in tickling interaction to confirm that multimodal interaction affect their brain responses.

2. Materials and methods

2.1. Participants

Data from a total of 28 infants (14 boys, M = 236.58 days, SD = 19.67, range = 210–264 days) were included in the study. An additional 10 infants (4 boys) participated in the experiment, but the relevant data were excluded for the following reasons: fussiness in the exposure phase (n = 6); not completing the entire test session (n = 1), and excessive noise within their EEG data (n = 3). All participants were neurologically typical, full-term (between 37 and 42 weeks of gestation) Japanese infants. Parents of infants gave informed consent and the study protocol was approved by the Ethics Committee of the Web for Integrated Studies of the Human Mind, Japan (WISH, Japan).

2.2. Stimuli for the test phase

We used 2 pseudowords (/topi-topi/ and /beke-beke/) as the stimuli for the test phase. The words consisted of the repetition of 2 moras, because the Japanese words typically used during a tickling interaction is /kocho-kocho/, which also involves the repetition of 2 moras. The stimuli used were recordings of the voice of a female experimenter who tickled the infants during the exposure phase. She did not know the purpose of the present study, and spoke each target word repeatedly in an infant-directed speech manner. Words were recorded at a 22.05-kHz sampling rate (in 16-bit monaural format) using a digital recorder in a soundproof chamber. After recording, another experimenter chose 2 different types of prosody per word, which were considered to reflect the most natural prosody. We prepared 2 different prosodic types in order to maintain the infants' attention during the test phase. The auditory stimuli presented to each infant therefore consisted of a total of 4 stimuli (2 words with 2 natural prosodic patterns). The auditory stimuli were controlled for the following parameters: the average fundamental frequency (F0), pitch maximum (F-Max), frequency range (F-range), and duration (Supplementary Information Table S1). The intensity of the auditory stimuli was adjusted across stimuli by equalizing the root mean square power of all sound files. These stimuli were presented to participants at around 50.15 dB sound pressure level (SPL).

2.3. Procedure

The experiment had 2 phases: an exposure phase (during which infants and an experimenter interacted), followed by a test phase (during which infants only heard words via a speaker) (Table 1). Before the exposure phase, an EEG cap was placed on the infants' heads, in order to shorten the time interval between these 2 phases (the mean time interval was 2 min). In our pilot test, we tried to record the infants' EEG during both the exposure and test phases to analyze the relationship between them. However, infants moved largely in the exposure phase, since they were highly interested in a dynamic social interaction. If we restrained infants' body movement, the interaction became unnatural. Therefore, we set an exposure phase separate from the test phase, and we measured the EEG in only the test phase.

2.3.1. Exposure phase

The exposure phase took place with infants seated on their caregiver's lap in a quiet room. Prior to the experiment, the experimenter played with the infants for a few minutes to build a rapport with them. Once the experiment commenced, the experimenter—sitting face-to-face with the