

Externally and internally controlled attention in infants: an EEG study

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Abstract

This work was designed to investigate EEG indices of Internally and Externally Controlled Attention in infancy. EEG was recorded in 15 infants aged 7–8 months under three experimental conditions: (1) visual attention to a new stimulation (Externally Controlled Attention or baseline condition); (2) attention guided by internal cognitive schemata during 'anticipatory' phase of the peek-a-boo game (Internally Controlled Attention); and (3) 'reappearance' phase of the peek-a-boo game when the experimenter talked and smiled to an infant (reappearance). The relative power (RP) in 4–5 single-Hz theta sub-band increased under both phases of the peek-a-boo game. The reactive changes of 4–5 single-Hz RP at prefrontal and frontal leads under the Internally Controlled Attention condition positively correlated with the total time during which an infant was able to maintain ICA. The RP in 5–6 single-Hz theta sub-band significantly increased only under the Internally Controlled Attention condition and did not correlate with the total time of this type of attention. The results support the concept of 'Diffuse Theta-Response System' that is active during expectancy and effortfully focused attention. In contrast to theta, the RP in 6–7, 7–8, and 8–9 single-Hz bands decreased during both phases of the game. The decrease was maximal at precentral leads and most probably reflected blockage of the sensorimotor (μ) rhythm due to higher motility and muscular tension in the game situation. It is concluded that EEG is an adequate vehicle for investigation of brain mechanisms of attention and voluntary control in infants. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Research on the nature of infant attention has generated considerable interest over the last decade. In contemporary developmental psychophysiology sustained attention in infancy is not considered as a unitary phenomenon but multiple processes involved in attention control are suggested (Posner and Presti, 1987; Posner and Raichle, 1994). A newborn infant immediately after birth is able to direct attention towards specific aspects of visual stimulation in the center of the visual field. The development of visual attention is supported by the maturation of four neural pathways that become sequentially functional from birth to 6 months of age (Johnson, 1990). The more active type of attention is less dependent on the characteristics of incoming stimulus information (e.g. complexity or novelty). It is associated with task demands and inner control processes and emerges starting at 7–8 months. This mode of attention control demands the ability to avoid the influence of immediate sensory stimuli in the environment (Posner and Presti, 1987). The adequate inhibitory control of current sensory events can manifest itself as an anticipation of an event for the purpose of responding (so called anticipatory attention) (Ruff, 1990). The appearance of such attention coincides with developmental leaps in other cognitive domains: marked improvement in understanding of object permanence, enhancement of retrieval memory, the emergence of fear of strangers and separation anxiety. The emergence of these behaviors also involves the elements of voluntary control over perception and action (Rothbart and Posner, 1985; Diamond, 1990). Diamond (1990) proposed that the ability for a memory-based intention to override habit and to exercise choice emerges during this developmental period. The critical improvement of infant cognitive abilities occurring at approximately 8 months of age is caused by the maturational spurt at development of the cerebral cortex (Goldman-Rakic, 1987) and, in particular, the development of dorsolateral prefrontal cortex (Diamond, 1990). The dorsolateral prefrontal cortex (as well as parietal cortex) is also known to play an important role in the higher

levels of attention control (Posner and Presti, 1987; Robbins, 1996).

According to the multiple activation model (Pribam and McGuinness, 1975; Zeef et al., 1990), involuntary attention is driven by properties of the stimulus, such as its novelty and complexity and it is regulated by the arousal (ascending reticular formation) system. The upper level of attention that requires active inner control and inhibition of irrelevant environmental stimuli is controlled by the activity of limbic structures and associative cortical areas.

We hypothesized that in infants the attention controlled by the current sensory environment and the Internally Controlled (in particular, anticipatory) Attention have different neural origins. EEG is shown to be an appropriate technique for studying the contribution of different attention control systems to the performance of cognitive tasks in adults (Ray, 1990; Barcelo et al., 1995). However, much less is known about the EEG indices of different types of attention in infancy. Recently, the adequacy of EEG techniques for studying the brain-behaviour relationships during the first year of life has been affirmed (Fox and Davidson, 1986). However, the infant EEG is commonly studied in the so-called 'background' condition. It does not allow to assess the brain activity underlying sustained attention involved in the performance of cognitive tasks.

The present study examined EEG indices of task-dependent cortical activity in two attention states: sustained visual attention to a real sensory object (Externally Controlled Attention) and Internally Controlled Anticipatory attention. The peek-a-boo game was used to elicit the latter type of attention (Ruff, 1990). During this game the experimenter talked and smiled to an infant and then hid behind the screen for several seconds. During this 'disappearance' phase most of the infants eagerly concentrated their attention on the place where the experimenter disappeared and anticipated her reappearance. There are several reasons why such an anticipatory attention is appropriate for studying the higher level of the attention control system in 7–8-month-old infants. First, this behavioral task is relevant to the major achievements in cognitive development oc-

curing around the eight month of life. Second, infant sustained attention in this task requires 'representation of information in the absence of a stimulus event' (Posner and Raichle, 1994). Therefore it is based on the activity of the upper brain mechanism of focused attention — 'the effort' (Zeef et al., 1990) or 'anterior control system' (Posner and Raichle, 1994). These mechanisms regulate the input of information to the cortex by differential activation of cortical neural networks and by inhibition of distraction stimuli.

The infant sustained attention at the peek-a-boo game is usually accompanied by positive emotions. Thus, in normal infants it is difficult to separate empirically cognitive effort from emotional tension because mechanisms of emotional and cognitive regulation are strongly interrelated (Sroufe and Waters, 1976; Cicchetti and Hesse, 1983). The emotional reactions provoke pronounced changes in infant EEG (Kugler and Laub, 1971; Maulsby, 1971a; Nikitina et al., 1987; Stroganova and Posikera, 1993). To verify the EEG changes related to the internally controlled attention mode rather than to emotional arousal, we added the third condition to the experimental design: the expected-person reappearance after a period of sustained anticipatory attention. Although the 'person reappearance' is the emotion evoking condition, it does not require the ability to maintain attention in the absence of the attended object and to inhibit interference.

We anticipated that the EEG parameters would differentiate the attention states with the external and internal locus of control. We also expected that these parameters would correlate with behavioural capacity to maintain anticipatory attention.

2. Method

2.1. Subjects

The initial sample consisted of 46 infants aged 7–9 months selected for the absence of serious medical and neurological problems. All infants were Caucasian twins. In this study we only analysed the data from one member of the twin pair.

Fifteen infants (7 boys and 8 girls aged from 7 months 19 days to 9 months 10 days of chronological age) were included into the final sample according to the behavioural criteria described below. All infants were born on the 34–40 week of gestation (mean 37 weeks) with birth weight within the limits of 2300–3500 g (mean 2640 g). The ages corrected for the period of gestation ranged from 6 months 26 days to 8 months 19 days. After the correction for prematurity all subjects had Bayley Mental Developmental scores higher than 83 (mean 104 ± 12.3) and Bayley Psychomotor Developmental Scores higher than 96 (mean 110 ± 10.4).

2.2. Design

An infant was sitting on his/her mother's lap throughout the experimental session. Infant behaviour was videotaped. EEG, EOG and ECG were registered under three conditions varying with respect to the type of attention and arousal.

In the first condition, an infant looked at the adult blowing soap bubbles 1.5–2 m away from the infant. All infants remained motionless for at least 30 s and looked at the subject without overt signs of emotional expression (smile, frown, vocalisation, etc.). We call this condition the Externally Controlled Attention (ECA).

The second and the third conditions constituted the two consequent phases of the peek-a-boo game. During this game the experimenter smiled and talked to an infant and then hid behind a screen for approximately 8 s. After this period, she reappeared for at least 10 s smiling and talking to the infant again. The game was terminated if the infant started to fuss or cry. In this case the experimenter communicated with the infant to soothe him/her. Ten trials were performed for each subject.

Under the second condition an infant anticipated the reappearance of the experimenter during the period when she hid behind the screen. We consider this behaviour as Internally Controlled Attention (ICA).

Under the third condition an infant looked at the experimenter during her reappearance after

the period of anticipatory attention in the peek-a-boo game. This condition is designated as reappearance (REAP).

The infant anticipatory attention behaviour during the 'person disappearance' period was analysed on the basis of video records. The behaviour was coded using the following behavioural measures: the duration of visual orienting towards the place where the person disappeared, the duration and frequency of distractions accompanied by the gaze aversions, turning away, and diffuse movements. According to these measures, three behavioural patterns were determined. The first pattern was the sustained anticipatory attention highly tolerant to distraction. Uninterrupted visual orienting for at least 5 s to the place where the person disappeared served a criterion for this pattern. The second pattern was that of transient attention with irregular short periods of distraction and repeated orienting to the place of the experimenter's disappearance. The third pattern constituted the lack of visual anticipatory attention, when the infant turned away immediately or 2–3 s after the person's disappearance.

The fifteen out of 46 subjects who exhibited the first behavioural pattern (sustained anticipatory attention) in at least two trials and had artefact-free EEG during these trials were included in the final sample. In these 15 subjects artefact-free EEG was also acquired under ECA conditions. For 12 of them artefact-free EEG was obtained under REAP conditions.

For each of 15 subjects the total time of anticipatory attention was calculated across all 10 trials regardless of its duration in each trial. EEG records corresponding to at least 5 s of uninterrupted anticipatory attention were selected for further analysis.

2.3. Recording and processing of psychophysiological data

Electrodes for EEG recording were placed at Fp1, Fp2, F7, F8, T5, T6, P3, P4, O1, O2 (according to the International Electrode (10–20) Placement System) and at the precentral positions (pC3, pC4), exactly between frontal (F3, F4) and central (C3, C4) derivations. The pC3 and pC4 positions

were selected according to the correction of electrode placement for infant brains (Blume et al., 1974). All data were recorded monopolarly against linked ears. Electrodes for recording horizontal EOG were placed at the outer canthi of both eyes. Electrodes for electrocardiogram recording were positioned at the inner sides of both forearms.

EEG, EOG and ECG were recorded on Nihon Kohden 4217 G using a time constant of 0.1 and a high frequency cut-off of 30 Hz. Data were stored on FM tape recorder Teak XR-510 and digitised off-line at 128 Hz. The digitised EEG was visually checked for eye movements and motor artefacts. Periods of artefact were eliminated from subsequent analyses. Fast Fourier Transform was performed using 5-s epoch length and the Kaizer–Beissel window.

For different subjects the number of ICA 5-s EEG epochs subjected to averaging varied from two to four depending on two conditions. First, it was limited by the number of trials in which the infant maintained anticipatory attention for at least 5 s. Second, it was limited by the number of artefact-free epochs with this pattern of attention. The number of ICA epochs analysed for each trial was limited by the duration of the 'disappearance' phase and was not more than one.

For the REAP condition 2–4 artefact-free 5-s EEG epochs following the 'successful' ICA trials were averaged for each infant. Only one artefact-free 5-s REAP epoch was sampled for each trial.

Four to six 5-s epochs (20–30 s) of artefact-free EEG were sampled for each infant in the case of the ECA condition.

Relative spectral power (RP) at 4–5, 5–6, 6–7, 7–8 and 8–9 single-Hz bands was computed from the spectra normalised in the range of 1–15 Hz. The appropriate transformation [$\log_{10}(x/100 - x)$] was applied to improve the normality of the data.

For each experimental condition the mean heart period (R-R interval) was analysed during the time periods selected for EEG analysis.

2.4. Statistical analyses

The ICA and REAP RP Change Scores were

calculated according to the following formulae $(RP_{ICA} - RP_{ECA})/RP_{ECA} \times 100$ and $(RP_{REAP} - RP_{ECA})/RP_{ECA} \times 100$, where RP_{ECA} , RP_{ICA} , and RP_{REAP} are RP under ECA (baseline), ICA, and REAP conditions respectively. This procedure is similar to calculation of the Event-Related Desynchronization described by Aranibar and Pfurtscheller (1978). Spearman rank correlation was used to reveal the relationship between the total time of ICA and RP Change Scores under the ICA and the REAP conditions.

Three-way ANOVAs were performed for each single-Hz frequency band. The factors and their levels were Condition (ECA, ICA, REAP), Hemisphere (left, right) and Derivation [location of the electrodes that are grouped for prefrontal (Fp1, Fp2), frontal (F7, F8), precentral (pC3, pC4), temporal (T5, T6), parietal (P3, P4) and occipital (O1, O2) regions]. Extended Change Scores ANOVA was carried out to analyse the difference between the RP reactive changes in 4–5 and 5–6 single-Hz frequency bands under the ICA condition.

All ANOVAs were repeated measures ANOVAs having factors with levels exceeding two. Therefore Greenhouse–Geisser epsilon values were applied to correct for the lack of sphericities in the covariance matrices. Original degrees of freedom, epsilon values and corrected *P*-values are reported throughout. Contrasts of group means were used as post-hoc tests.

3. Results

3.1. Behaviour and mean heart period dynamics

The total time of ICA across 10 trials varied from 10 to 60 s for different subjects.

The behavioural signs of emotional expressions (smile, vocalisation) during ECA were absent in all subjects. The overt signs of emotions were not observed also during ICA under the person disappearance condition. REAP was accompanied by smiles in 7 out of 15 subjects.

One-way ANOVA revealed significant effect for Condition ($F_{2,22} = 5.9$, $\epsilon = 0.822$, $P < 0.02$) for heart period (Fig. 1). Inspection of the respective means suggests that heart period decreases during both phases of the peek-a-boo game relative

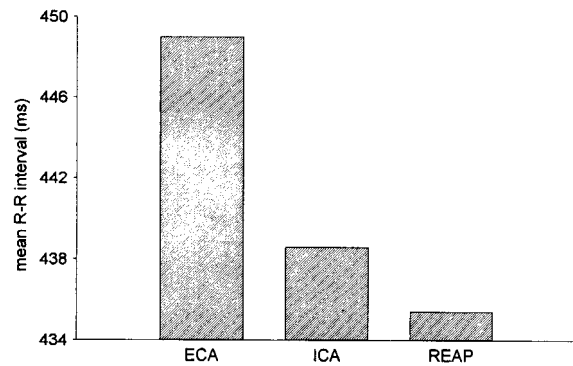


Fig. 1. Mean heart period (R-R interval) under three experimental conditions: ECA — visual attention to an object outside the peek-a-boo game (the baseline); ICA — internally controlled attention during expectation of the person hidden behind the screen in the peek-a-boo game; REAP — attention to the reappeared person in the peek-a-boo game. There is a significant decrease of mean heart period during both phases of the peek-a-boo game (ICA, REAP) as compared to the ECA condition.

to the baseline (ECA) condition ($F > 5.5$, $P < 0.05$).

3.2. EEG data

A sample of infant EEG is presented in Fig. 2. Under the baseline (ECA) condition the most prominent regular rhythmic activity was usually seen in the 6–8 Hz frequency range at the precentral recording sites (Fig. 2A). Visual inspection of EEG records revealed marked increase of activity in the theta frequency range (4–6 Hz) and suppression of precentral 6–8 Hz rhythmic activity under both conditions of the peek-a-boo game (Fig. 2B).

The results of the single-Hz RP ANOVAs indicated that visually detectable changes of EEG rhythmic activity were highly significant. The ANOVAs results are listed in Table 1. The significant effects for relative power in the theta band (4–5, 5–6 Hz) will be considered first.

The main effect for Condition in the 4–5 Hz frequency range was due to higher RP under both ICA ($F_{1,11} = 26.2$, $P < 0.0004$) and REAP ($F_{1,11} = 7.3$, $P < 0.03$) conditions relative to the baseline (Fig. 3). The difference between these two conditions of the peek-a-boo game in this single-Hz

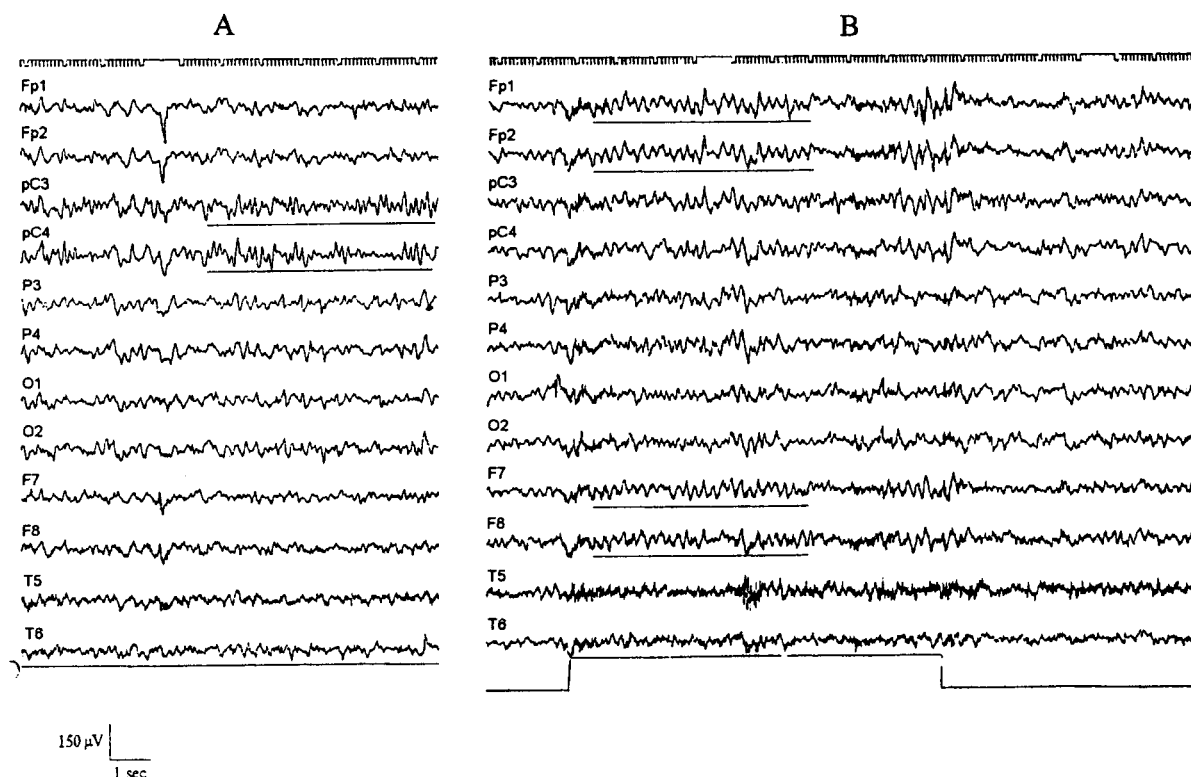


Fig. 2. EEG of one subject who demonstrated prolonged duration of anticipatory attention across ten trials (60 s). A: The baseline condition. The rhythmic 6–8-Hz activity at precentral leads (mu-rhythm) is underlined. B: The peek-a-boo game. The upward deflection of the mark under EEG channels corresponds to the period of anticipatory attention. The downward deflection of the mark corresponds to the 'person reappearance' condition. The 4–5-Hz rhythmic activity (theta rhythm) during anticipatory attention is underlined. Theta activity is also visually detectable under the 'person reappearance' condition.

band was marginally significant ($F_{1,11} = 4.3$, $P = 0.062$), with higher RP observed during ICA. Thus,

the relative power in 4–5 single-Hz band increased during both phases of the peek-a-boo

Table 1
The results of single-Hz RP ANOVAs

	4–5 Hz	5–6 Hz	6–7 Hz	7–8 Hz	8–9 Hz
Condition (CON)	$F_{2,22} = 11.84^{**}$ $\epsilon = 0.98$	$F_{2,22} = 11.75^{**}$ $\epsilon = 0.96$	$F_{2,22} = 5.31^*$ $\epsilon = 0.75$	$F_{2,22} = 8.12^{**}$ $\epsilon = 0.98$	$F_{2,22} = 4.54^*$ $\epsilon = 0.961$
Derivation (DER)		$F_{5,55} = 5.07^{**}$ $\epsilon = 0.96$		$F_{5,55} = 3.43^*$ $\epsilon = 0.61$	
Hemisphere (HEM)	$F_{1,11} = 5.82^*$				
CON \times DER			$F_{10,110} = 5.96^{**}$ $\epsilon = 0.544$	$F_{10,110} = 9.74^{**}$ $\epsilon = 0.442$	
HEM \times DER	$F_{5,55} = 3.79^*$ $\epsilon = 0.590$				

* = $P < 0.05$; ** = $P < 0.01$

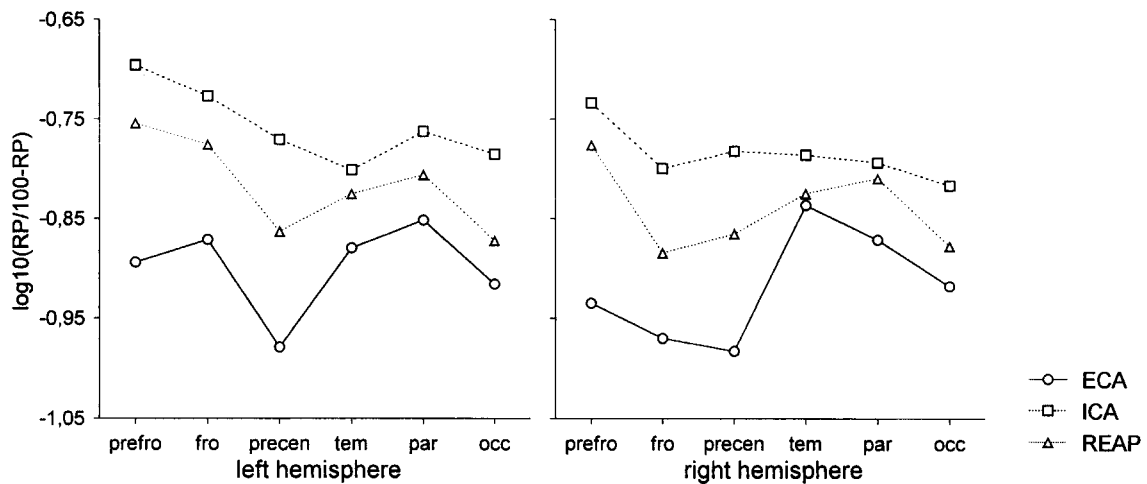


Fig. 3. The 4–5-Hz RP under three experimental conditions. The RP is higher during both phases of the peek-a-boo game (ICA, REAP) as compared with the baseline (ECA) condition.

game as compared to the baseline condition. The theta increase in this single-Hz frequency band was most prominent under the ICA condition. The Condition \times Derivation interaction was not significant ($F_{10,110} = 1.24$, $P = 0.27$). However, the planned comparisons revealed a tendency for the RP increase to be more significant at anterior recording sites for both ICA (prefrontal, $F_{1,11} = 17.4$, $P < 0.002$; frontal, $F_{1,11} = 6.0$, $P < 0.04$; pre-

central, $F_{1,11} = 16.2$, $P < 0.002$; occipital, $F_{1,11} = 5.9$, $P < 0.04$; n.s. at parietal and temporal) and REAP (prefrontal, $F_{1,11} = 6.0$, $P < 0.04$; precen- tral, $F_{1,11} = 5.7$, $P < 0.04$; n.s. at frontal, temporal, parietal and occipital) conditions. The significant Hemisphere \times Derivation interaction which is not plotted here revealed higher RP at prefrontal ($F_{1,11} = 11.2$, $P < 0.006$) and frontal ($F_{1,11} = 12.3$, $P < 0.005$) recording sites of the left hemisphere.

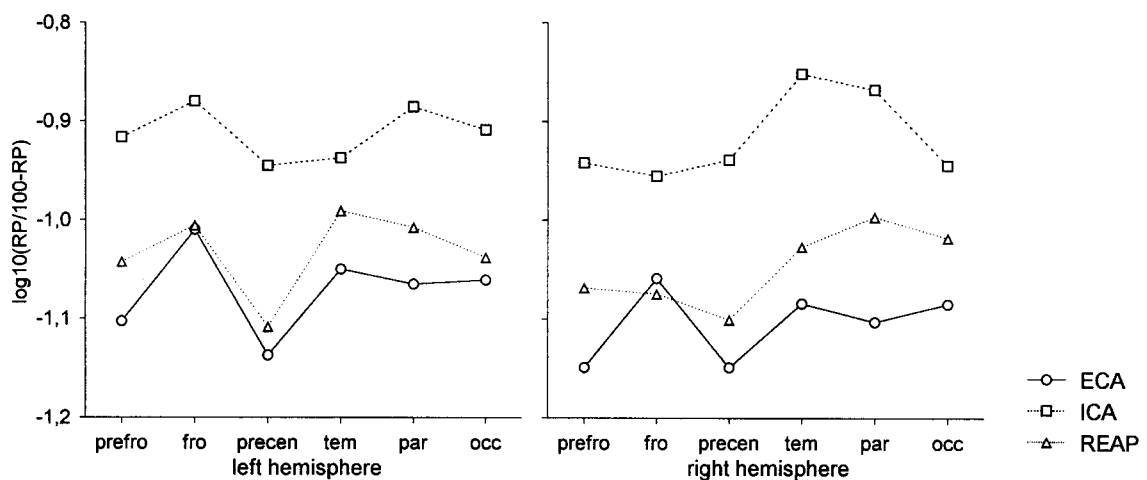


Fig. 4. The 5–6-Hz RP under three experimental conditions. The RP is higher under ICA condition than under both ECA and REAP conditions.

For the 5–6 single-Hz band the main effect for Condition was also significant. During the ICA, RP was higher than under both the ECA ($F_{1,11} = 19.2$, $P < 0.002$) and REAP ($F_{1,11} = 10.95$, $P < 0.007$) conditions (Fig. 4). The difference between the ECA and REAP was not significant ($F_{1,11} = 2.12$, $P = 0.17$). These results demonstrate two interesting effects. First, during the ICA, RP significantly increased in both upper (5–6 Hz) and lower (4–5 Hz) theta sub-bands. Second, under the REAP condition there was no 5–6-Hz RP increase observed in the lower theta sub-band.

Both 6–7 Hz and 7–8 Hz ANOVAs showed a significant main effect for Condition. Because in both cases the factor Condition was involved in highly significant interactions Condition \times Derivation, it can be best described in the context of this interaction. The respective means of Condition \times Derivation interactions for the two single-Hz bands are plotted in Fig. 5A,B. They indicate that in both single-Hz bands the interactions were due to lower RP at anterior leads during the ICA and the REAP conditions in comparison with the baseline (all $F > 13.9$, $P < 0.004$). Thus, Condition \times Derivation interactions showed that, in contrast to posterior recording sites, anterior recording sites exhibited pronounced 6–8 Hz power suppression under both conditions of the peek-a-boo game.

The 8–9-Hz ANOVA also showed significant main effect for Condition. This is due to lower RP during ICA than during ECA ($F_{2,22} = 11.2$, $P < 0.007$) (Fig. 5C). Thus, RP in this single-Hz band decreased under the Internally Controlled Condition, similarly to RP in the 6–7 and 7–8 single-Hz bands.

3.3. The theta RP change scores during the Internally Controlled Attention condition

The analysis of respective means points to the topographical difference of RP reactive changes in two theta subbands under the ICA condition (Figs. 2 and 3). The significance of the topographical difference of ICA Change Scores was tested using three-way ANOVA. The factors were Sub-band (4–5, 5–6 Hz), Hemisphere, and Derivation.

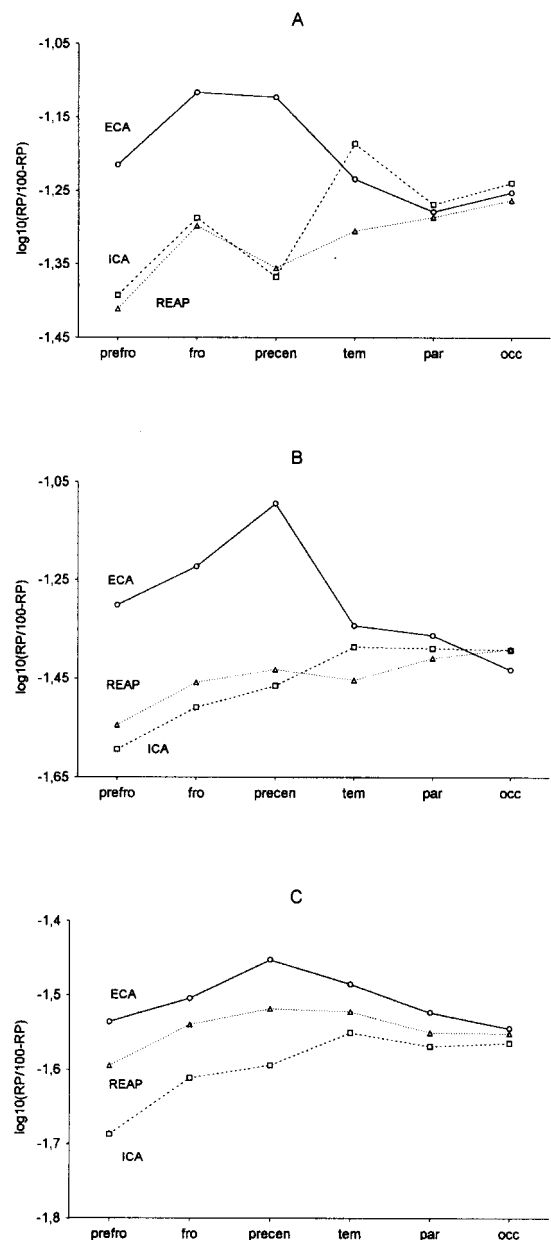


Fig. 5. The RP of three single-Hz bands related to mu rhythm in three experimental conditions: interaction between factors CONDITION and DERIVATION. A: 6–7-single-Hz band; B: 7–8-single-Hz band; C: 8–9-single-Hz band. The 6–7-Hz and 7–8-Hz RPs at anterior leads are higher during the baseline (ECA) condition as compared to both conditions of the peek-a-boo game (ICA, REAP) (A,B). The dynamic of 8–9-Hz RP is similar to the state-related changes of 6–7-Hz and 7–8-Hz RP (C). Note that the state-related dynamic of 6–9-Hz RP is opposite to the theta RP changes.

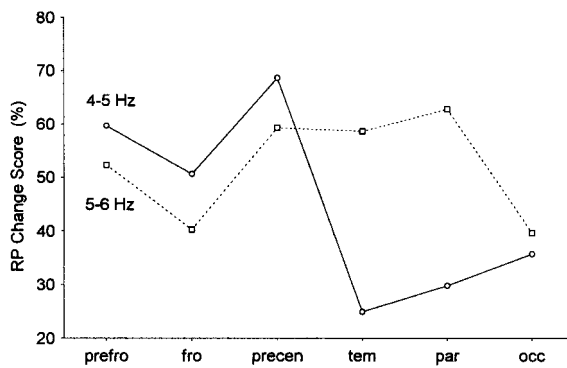


Fig. 6. The ICA Change Scores for 4–5-Hz and 5–6-Hz bands: interaction between factors BAND and DERIVATION. At temporal and parietal leads the 5–6-Hz Change Scores are higher than 4–5-Hz Change Scores.

The Change Scores ANOVA showed one significant Subband \times Derivation interaction ($F_{5,70} = 3.43$, $\epsilon = 0.490$, $P < 0.05$) which is plotted in the Fig. 6. This interaction was due to higher 5–6 Hz Change Scores at temporal ($F_{1,14} = 5.0$, $P < 0.05$) and parietal ($F_{1,14} = 4.92$, $P < 0.05$) recording sites as compared with 4–5 Hz Change Scores. Thus, topographical distribution of RP reactive changes in 4–5 and 5–6 Hz theta subbands differed under the ICA condition.

3.4. Correlation between reactive changes of EEG RP and duration of Internally Controlled Attention

Several positive correlations between RP Change Scores and the total time of ICA were significant (Table 2). These correlations grouped around the frontal lobe for the 4–5 single-Hz band and were more randomly distributed for 7–8 and 8–9 single-Hz bands.

None of the correlations between RP Change Scores under the REAP condition and the total time of ICA were significant.

4. Discussion

4.1. Theta (4–6 Hz) band

Theta activity in the 4–5 Hz sub-band increased during both stages of the peek-a-boo game comparing to the baseline (ECA) condition. The RP in 5–6 Hz theta sub-band also increased

Table 2

Spearman correlations between ICA Change Scores and the total time of anticipatory attention in five single-Hz bands

	4–5 Hz	5–6 Hz	6–7 Hz	7–8 Hz	8–9 Hz
Fp1	0.67**	–0.04	0.01	0.58*	0.70**
Fp2	0.66**	0.05	0.15	0.41	0.35
F7	0.59*	0.45	–0.30	0.13	0.22
F8	0.70**	0.44	0.03	0.51	0.09
pC3	0.43	0.13	–0.15	0.46	0.44
pC4	0.34	–0.26	–0.29	0.23	0.19
T5	0.21	0.40	0.15	0.63**	0.31
T6	0.33	0.31	0.05	0.39	0.39
P3	–0.13	0.15	0.39	0.43	0.01
P4	0.04	–0.14	0.28	0.46	0.01
O1	0.11	–0.10	0.14	0.68**	–0.36
O2	0.37	0.27	0.20	–0.02	–0.16

* – $P < 0.05$; ** – $P < 0.01$

under these conditions, but this increase was significant only under the ICA condition (Figs. 3 and 4).

Theta activity is very abundant in infant EEG. Therefore the theta rhythm is often considered as a precursor of adult alpha rhythm (Smith, 1939, 1941; Markand, 1990). Nevertheless, the ‘functional topography’ approach to the analysis of state-related changes of infant EEG spectra showed that alpha and theta rhythms are distinct EEG components during the second half-year of life (Stroganova and Posikera, 1993). They have different frequency (4–6 Hz for theta and 6–9 Hz for alpha), functional reactivity, and topographical distribution.

Increase in theta activity is known to accompany positive emotional reactions in infants (Maulsby, 1971b; Kugler and Laub, 1971; Nikitina et al., 1987; Stroganova and Posikera, 1993). Although the overt signs of emotional reactivity were absent under both ECA and ICA conditions, the mean heart period was shorter under the latter condition. The length of the heart period did not differ between ‘anticipatory’ and ‘reappearance’ phases of the game, although only the latter phase was accompanied by overt emotional expressions. Thus, the emotional arousal increases during both phases of the game. Therefore the theta increase under both these conditions might result from the emotional reaction.

Theta synchronisation during emotional excite-

ment has also been observed in adults (Adey et al., 1967; Cohen et al., 1976; Larbig, 1994). In adults, theta increase was also found to be related to cognitive processes, such as learning (Lang et al., 1987), memory (Klimesch et al., 1994), mental effort (Kornhuber et al., 1990), and problem solving (Vogel et al., 1968; Ishihara and Yoshii, 1972; Mizuki et al., 1980). The amount of theta activity in the EEG positively correlated with performance of the tasks demanding effortful concentration of attention, such as detecting specified digit triads in a random digit series (Daniel, 1967), solving difficult cognitive task (Vogel et al., 1968), difficult motor tracking and concept formation tasks (Lang et al., 1987).

The results of the present study also suggest that in 7–8-month-old infants the theta increase during anticipatory attention is related not only to emotional excitement, but also to the cognitive complexity of the situation, in particular, to effortful concentration of attention guided by internal representation. Two types of evidence support this conclusion. First, despite the lack of overt behavioural signs of emotions during the 'anticipatory' phase of the game, the increase of RP in the 4–5 sub-band under this condition was even more pronounced than during the reappearance of the expected person which was followed by smiles in some infants. The 5–6 Hz RP increased only during anticipatory attention. Second, there was a positive correlation between the enhancement of 4–5 Hz RP at prefrontal and frontal derivations during ICA and the total time of this type of attention. If this correlation could be explained by the higher emotional arousal in infants who more eagerly participated in the peek-a-boo game, one could also expect positive correlations between the duration of Internally Controlled Attention and the magnitude of theta increase during the 'reappearance' phase of the game. However, there were no significant correlations between the total time of ICA and RP Change Scores under the REAP condition.

It is especially interesting that the relationship between the total time of ICA and 4–5 Hz RP Change Scores was found exclusively for prefrontal and inferior frontal (F7, F8) derivations (Table 2). The critical role of prefrontal cortex in the ability 'to bridge temporal gaps in the percep-

tion-action cycle' (Fuster, 1990) and to inhibit interference (Posner and Presti, 1987; Diamond, 1990) is well established. Lang et al. (1987) also found a positive correlation between theta spectral power at frontal and prefrontal leads and success in learning difficult manual tracking and concept formation tasks in adults. Performance of these tasks, as well as maintenance of ICA by 7–8-month-old infants, requires effortful concentration of attention. This mode of attention is controlled by higher levels of brain attentional system that includes prefrontal cortex (Posner and Presti, 1987). We hypothesise that in infants the enhancement of theta rhythm over the frontal lobes during ICA is associated with activity of the anterior attentional system.

The functional significance and neurophysiological origin of the theta activity observed during cognitive and perceptual processes are intensively discussed in contemporary psychophysiological literature (Demiralp and Başar, 1992; Lopes da Silva, 1992; Başar and Schürmann, 1994; Demiralp et al., 1994; Diamond and Rose, 1994; Schürmann and Başar, 1994). Based on the review of experimental studies, Demiralp et al. (1994) concludes that the limbic system and associative areas of the cerebral cortex generating theta appears to be unified into the single system. The concept of 'Diffuse Theta-Response System' (Başar et al., 1991; Demiralp et al., 1994) implies that the increase of theta activity over the human associative cortex reflects general responsiveness of the hippocampal-frontal-parietal circuit during effortfully focused attention and expectancy and leads to enhancement of neuronal plasticity. We suggest that theta increase observed during Internally Controlled (anticipatory) Attention in infants during the peek-a-boo game reflects activity of this 'Diffuse Theta-Response System' that is related to expectancy and effort.

The emotional and cognitive roots of the theta increase during the peek-a-boo game in infants cannot be completely separated. Although theta increase in the 4–5 Hz sub-band was highest during the 'anticipatory' phase of the peek-a-boo game, it was also prominent during the 'reappearance' period. The latter condition did not require effortful concentration of attention, but it was associated with an elevated emotional level.

One can hypothesize that the theta increase is partially related to non-specific energetic processes. Studies on animals suggest that both hippocampal EEG activity in the theta range and hippocampal long-term potentiation, that is known to be involved in learning and memory, are sensitive to endogenous arousal level (Maren et al., 1994). The brain processes leading to generation of theta electrical activity during performance of a difficult task have been proposed to create the endogenous arousal level optimal for cognitive functioning (Vinogradova, 1975). One of the candidates for these brain processes is the activity of the upper attention control system [the effort system in Pribram and McGuinness (1975) scheme]. This system uncouples the most primitive relationship between stimulus and reaction (as in the case of ICA during peek-a-boo game) and optimizes the endogenous arousal level according to the needs of the task. Although the theta increase is related to elevated endogenous arousal level, it is presumably induced by activity of different neural mechanisms in the case of the anticipatory attention and the 'person reappearance' situations. In the former case, the positive correlation between the magnitude of the low theta increase and the anticipatory behaviour may be explained by higher activity of the upper attention control system in those infants who are able to maintain ICA over the longer time intervals.

The difference between reactivity of 4–5 and 5–6 Hz theta sub-bands is of special interest. The high (5–6 Hz) theta sub-band most sharply differentiated the anticipatory attention from attention to the reappeared person. The increase of RP in this sub-band was significant only during the 'anticipatory' phase of the game. One might believe that the difference between reactivity of low and high theta sub-bands results from increase of theta frequency during effortfully focused attention. The increase of theta frequency may be caused by increase of arousal. Animal-based studies suggest that increase of theta frequency accompanies ascending reticular formation activation (Vinogradova, 1975). However, the difference between reactive changes in 4–5 Hz and 5–6 Hz sub-bands during ICA could not be attributed exclusively to increase of theta frequency due to higher arousal level for two rea-

sons. First, a marked topographical distinction was observed between RP reactivity in two theta sub-bands (Fig. 6). The 4–5 Hz RP increase was more prominent over the anterior cortex, whereas the 5–6 Hz RP increase was more generalised. Second, in contrast to the 4–5 Hz theta sub-band, the 5–6 Hz theta sub-band was not related to the general duration of ICA. These two facts suggest that 4–5 Hz and 5–6 Hz RP reactive changes reflect different processes.

4.2. 6–9 Hz activity

In contrast to the sharp increases of 4–5 and 5–6 Hz activity during 'anticipatory' and 'reappearance' phases of the peek-a-boo game, 6–7 and 7–8 Hz rhythmic activity decreased during both these conditions as compared to the baseline. The decrease was most prominent at precentral recording sites where the maximal 6–8 Hz RP was observed under the baseline condition [Figs 2, 5 (A, B)]. Similar functional reactivity of 6–7 and 7–8 single-Hz frequency bands is likely to be determined by their common physiological origin. The rhythmic activity of alpha and beta frequency ranges recorded over the central and precentral cortex during a number of vigilance states in humans (Chatrian, 1976) and animals (Rougel-Buser et al., 1975) is called the sensori-motor or mu-rhythm. The frequency of mu-rhythm in 7–9-month-old subjects was shown to lie in the range between 6 and 9 Hz (Stroganova and Posikera, 1993). Mu-rhythm accompanies a motionless state and is related to inhibition of the sensori-motor input and output of the cerebral cortex (Rougel-Buser et al., 1975; Rougel et al., 1979). The decrease of RP in the mu band during both phases of the peek-a-boo game was most probably determined by higher motility and muscular tension under these conditions.

The 8–9 Hz RP also decreased during ICA relative to the baseline (Fig. 5C). Since RP values were low in this single-Hz frequency band, this band seems to be close to the upper border of the functional range of infant EEG and is also related to the mu rhythm.

Dawson et al. (1992) observed similar dynamics of 6–9 Hz rhythmic component of infant EEG. They found that anterior spectral power in this

range decrease during crying provoked by maternal separation as compared to the state of visual attention considered as the baseline. Our interpretation of anterior 6–9 Hz rhythm as sensori-motor (μ) rhythm suggests that this fact can also be explained by higher motility during crying than during the 'baseline' condition.

Sporadic, but significant positive correlations between RP in 7–8 and 8–9 single-Hz frequency bands and the general duration of ICA are difficult to interpret. Probably, they are explained by more prominent μ and alpha activity in the subjects who were able to maintain the ICA for a longer time. Sensori-motor rhythm reflects both the idle state of the sensori-motor cortex and active blocking of incoming impulses from somatic receptors, thus facilitating attention to stimuli of other modalities (Rougel-Buser et al., 1975; Rougel et al., 1979). The increase of alpha power is common for mental activity demanding memory updating and inhibition of immediate sensory input (Lehman and Koukkou, 1980; Ray and Cole, 1985). Considering the functional significance of sensory alpha and μ rhythms, longer persistence of ICA in infants with more pronounced sensory (μ and alpha) rhythms in this particular state may be related to more successful inhibition of interfering visual and somatosensory stimulation in these subjects.

In summary, the present study suggests that Externally Controlled Attention guided by a visible object and ICA guided by internal representation of an event have different neurophysiological mechanisms. It also shows that EEG recorded during ECA and ICA is a sensitive instrument for studying the neural mechanisms of attention and voluntary control over perception and action in infants.

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