Representing occluded objects in the human infant brain

Jordy Kaufman*, Gergely Csibra and Mark H. Johnson

Centre for Brain and Cognitive Development, School of Psychology, Birkbeck College, University of London, London WC1E 6BT, UK
*Author and address for correspondence: Department of Psychology, University College London, Gower Street, London WC1E 6BT, UK (j.kaufman@ucl.ac.uk).

Recd 17.04.03; Acceptd 18.06.03; Online 01.08.03

One of the most striking phenomena in cognitive development has been the apparent failure of infants to show ‘object permanence’ in manual reaching tasks although they show evidence for representing hidden objects in studies measuring looking times. We report a neural correlate of object permanence in six-month-old infants: a burst of gamma-band EEG activity over the temporal lobe that occurs during an occlusion event and when an object is expected to appear from behind an occluder. We interpret this burst as being related to the infants’ mental representation of the occluded object.

Keywords: object permanence; gamma oscillations; infant; egg

1. INTRODUCTION

Since the original observations of Piaget (1954), one of the most striking phenomena in cognitive development has been the apparent failure of infants to show ‘object permanence’. When an object is occluded by a cover, infants often behave as if it is no longer present: out of sight is out of mind. By contrast, studies measuring looking times reveal quite sophisticated reasoning about hidden objects, even in young infants (for a review, see Baillargeon 2001). In a previously separate line of research, sustained responses in neural circuits have been identified as a mechanism for maintaining representations of objects during a period of occlusion (Rainer & Miller 2000). In particular, gamma-band (*ca.* 40 Hz) activity in human adults has been associated with maintaining an object in mind (Tallon-Baudry *et al.* 1998). Although gamma-band activity can be recorded in infants (Csibra *et al.* 2000), it has never previously been used to investigate object permanence in development. In the present study, we measured infants’ electrophysiological responses to occlusion events at the age where reaching behaviour does not yet show evidence of understanding ‘object permanence’.

2. EXPERIMENT 1

Prior to examining neural activity, it was necessary to determine that our experimental stimuli were sufficiently realistic to be perceived as real objects by the infant participants. Therefore, we created digital video sequences of real objects involved in expected and unexpected events

and measured infants’ looking times to them in a traditional ‘violation of expectation’ paradigm (Spelke 1985).

(a) Material and methods

(i) Subjects

Twenty-one six-month-old infants (aged 163–195 days, mean age of 182.2 days) participated in this experiment. A parent of each infant participant gave informed consent prior to participation. This and all subsequent experiments were carried out in accordance with human subjects ethical guidelines mandated by the National Institute of Health (USA) and the Medical Research Council (UK). An additional seven infants were tested but are not included in the dataset owing to fussiness ($n = 3$), experimental error ($n = 3$) or a failure to engage visually with the stimuli ($n = 1$).

(ii) Stimuli

Each infant was shown sequences of video-recorded and digitally edited events depicting an object (a train engine) appearing, or failing to appear, out of a tunnel when it should or should not have been there. Infants were first familiarized with the situation by watching a repeating event in which the engine entered the screen and then went into, and reversed out of, the tunnel. Each familiarization cycle lasted for 6 s. The familiarization trial ended when infants had looked at the screen for a minimum of 30 s and then looked away from the monitor for at least 2 s, or until 120 s had elapsed. Following the single familiarization trial, four test events (expected appearance, unexpected appearance, expected disappearance, unexpected disappearance) were then presented in counterbalanced order. Each event cycle lasted for 6 s (which did not vary across the four video types). The train subtended a visual angle of 5.1° and it moved at a speed of 0.18° visual angle per second. Looking time (figure 1*a*) was measured from the point at which infants began to look continuously from the start to the end of the event sequence (thus providing certainty that they had witnessed the expected or unexpected aspects of the event). The event was repeated until infants looked away from the video monitor for 2 s. Longer looking times are thought to reflect greater information processing in infant behavioural research (Spelke 1985).

(b) Results and discussion

The mean looking time during familiarization was 80.1 s (s.d. = 33.1 s). Looking times to the test events are depicted in figure 1*b*. A 2×2 ANOVA (group $\times$ event type) on looking times yielded a significant interaction ($F_{1,20} = 4.9$, $p < 0.05$), while *t*-tests revealed a significant expected–unexpected looking time difference only within the disappearance condition ($t_{40} = 3.79$, $p < 0.005$).

Our results are consistent with earlier findings (Wynn & Chiang 1998) that infants are highly sensitive to the unexpected disappearance of an object (consistent with object permanence) but are less sensitive to an unexpected appearance. Several possible explanations for the appearance/disappearance discrepancy have been offered—including the idea that infants can infer the existence of two objects behind an occluder (Baillargeon 1994; Aguiar & Baillargeon 2002). Whatever the correct explanation for this result, experiment 1 demonstrated that infants react to our computerized stimuli as if they were watching real objects.

3. EXPERIMENT 2

In experiment 2, we measured the brain electrical activation (via an electroencephalogram, or EEG) of infants who were watching the disappearance events that we used in experiment 1. We proposed that gamma-band oscillatory activity might be present in the infant brain during object occlusion.

(a) Material and methods

Participants in this experiment were six-month-old infants ($n = 22$, aged 159–195 days, mean age of 178.0 days). An additional 45 infants were tested but were eliminated from the analysis owing to insufficient quantifiable trials ($n = 41$) or experimenter or technical

Figure 1. A schematic representation of the stimuli and results of Experiment 1. (a) Four films were created by digital editing and sequencing of three events: a toy train engine entering a tunnel, the engine leaving the tunnel and a hand lifting the tunnel revealing either the engine (appearance) or nothing (disappearance). According to the order of the last two phases, the appearance or disappearance of the engine was either expected or unexpected. (b) Mean looking times and standard errors. * Signifies statistical significance ($p < 0.005$).

errors ($n = 4$). During the experiment, infants viewed versions of the expected and unexpected disappearance films shown in experiment 1.

The films were modified in speed so that more cycles could be shown in a limited amount of time in which infants would comfortably attend to the events. The engine moved approximately twice as fast as in experiment 1 (38° visual angle per second) and an entire film cycle lasted 2.9 s. An EEG was recorded by a Geodesic Sensor Net (Tucker 1993) comprising 62 electrodes evenly distributed across the scalp. The vertex electrode (Cz) served as reference and the EEG was sampled at 250 Hz. The sequences were shown in a semi-random order with no event being shown more than three times consecutively. We recorded the EEG and videotaped the infants' looking behaviour for as long as they were willing to watch the com-

puter screen. Trials in which infants did not look at the entire sequence were excluded from the analysis. Induced gamma-band activation was analysed using established procedure (Csibra *et al.* 2000). Each infant contributed 22–80 (mean of 51.8) trials to their average (out of a mean of 86 presentations). We compared induced oscillations over right temporal areas between the two conditions during the part of the overall sequence in which the tunnel was lifted (figure 1a), a segment that was identical in both films (see figure 2a). Temporal and frontal sites were selected based on previous studies with human and non-human primates (Tallon-Baudry *et al.* 1998; Baker *et al.* 2001). Time-frequency activations were baseline corrected by subtracting the average activity during the last 92 ms of the engine entering the tunnel (figure 1a, left-hand panel). We selected this time-period as the baseline since it preceded any differences between the two conditions and because it does not contain any occlusion or partial-occlusion events (i.e. the train is always visible during the baseline period).

(b) Results and discussion

Results and analyses are illustrated in figure 2. Statistical analyses (t -tests) on the average gamma-band (20–60 Hz) activity in six consecutive 200 ms-long windows revealed higher activity in the unexpected than in the expected disappearance condition, both before and after the hand lifted the tunnel. Comparing gamma power in each of the two conditions with the preceding baseline revealed that, prior to the tunnel being lifted, gamma power was reduced in the expected disappearance condition. After the tunnel was lifted, there was significant enhancement of gamma-band activity in the unexpected disappearance condition relative to the baseline. These activity changes were largely restricted to the right, but not the left, temporal area (figure 2b), thus ruling out explanations related to muscle responses. Corresponding differences in gamma activity by condition were not apparent at frontal channels.

These results demonstrate a sustained period during which gamma power over the right temporal region was consistently higher while the object was occluded. This response persisted despite initial visual evidence to the contrary. We propose that this gamma activity provides a neural basis for object permanence in infants. Just before the tunnel was lifted, there was a relative (to baseline) decrease in gamma power in the expected disappearance condition. This suggests that the visual presence of the engine during the baseline phase partially activated gamma activity, which was then further strengthened during the later periods of occlusion in the unexpected disappearance condition. The maximal point of gamma power increase in the unexpected disappearance condition occurred *ca.* 500 ms after the initial lifting of the tunnel. One interpretation of this finding is that the infants' brain attempts to strengthen further the representation of the 'hidden' object to compete better with the (now) direct visual evidence to the contrary. From this standpoint, object permanence is the ability to maintain a sufficiently strong representation of the object, despite competing evidence from visual input (Munakata 2001).

4. EXPERIMENT 3

If the sustained gamma activity seen in experiment 2 is related to the representation of non-visible objects, it should also be evident in an ordinary event of temporary hiding, such as the expected appearance event in experiment 1. Furthermore, an alternative explanation for the increase in gamma activity following the uncovering event

Figure 2. Gamma-band activity in experiment 2. (a) Time–frequency analysis of the average EEG at three electrodes over the right temporal cortex (around T4) during the phase in which the tunnel was lifted showed higher activations when the object should have been below the tunnel. Black asterisks below the maps indicate a significant difference from baseline; red asterisks indicate a significant difference between conditions in the average gamma activity in 200 ms-long bins (t -tests: $*t_{21} > 2.00$, $p < 0.05$; $**t_{21} > 2.80$, $p < 0.01$). (b) A topographical map of the between-condition difference of gamma-band (20–60 Hz) activity during the occlusion-related peak gamma activity (from –400 to –200 ms) revealed a right-temporal focus. Circles signify right temporal electrode sites.

Figure 3. Gamma-band activity in Experiment 3. Statistical significance legend and topographical map parameters are the same as those in figure 2 (t -tests: $*t(14) > 2.25$, $p < 0.05$). Circles signify right temporal electrode sites.

is that it is correlated with the perception of an *impossible* event—and not directly related to object representation. To test these hypotheses we conducted another EEG experiment using only the appearance events.

(a) Material and methods

Infants ($n = 15$, aged 161–199 days, mean age of 178 days) watched expected and unexpected appearances in which a train was always revealed when the tunnel was lifted (see figure 1a). Each infant contributed 20–69 (mean of 40.0) trials to their average (out of a mean 69 presentations). In all other respects, the methods were identical to those of experiment 2.

(b) Results and discussion

The results and analyses are described and illustrated in figure 3. As in the first EEG experiment, an increased gamma power was evident at right temporal channels during the time and condition where the train should be hidden underneath the tunnel. There was no significant increase in gamma activity time-locked (i.e. temporally related) to the unexpected appearance event. As in experiment 2, the differences in oscillatory activity by condition were specific to right temporal channels.

The results of experiment 3 bolster the findings of experiment 2, that is, infants showed an increase in gamma activity at right temporal electrodes when the train should have been underneath the tunnel. However, and in contrast to the earlier experiment, following the phase in which the tunnel was lifted there were no significant differences in gamma power either between the two conditions or from the baseline. This supports the notion that the increase in gamma power following the lifting of the tunnel in the first EEG experiment is related to representing an object in the face of contradictory visual input.

In the latter EEG experiment, because the train was always revealed, there was no need to maintain a representation of the object independent of visual input. These results further advance the interpretation that gamma power in the right temporal area reflects active maintenance of occluded objects.

We concede that infants may not have seen the unexpected appearance sequence as 'impossible' because they could potentially infer that there were two trains underneath the tunnel. This leaves open the possibility that the second gamma burst in experiment 2 was related to an unsolvable violation of object knowledge. Although this theory deserves further investigation, we believe that our explanation, which posits a single process of object maintenance, is sufficient to account for the observed gamma activation pattern in these studies.

The occlusion-related neural activity also suggests an explanation for the findings of looking-time studies addressing infants' knowledge of objects. We suggest that increased looking time may reflect a conflict between the visual input and the current mental representation of an object. Whatever the exact neural basis of the effects that we have observed, our finding that increased gamma-band

activity is associated with the representation of hidden objects will inform fundamental issues about how infants process their visual world.

Acknowledgements

J.K. was supported by postdoctoral fellowships from the National Science Foundation (INT-9901349), National Institute of Child Health and Human Development (F32 HD08568-01), the British Academy (SG-31088) and Sackler Institute. Financial support was also provided by the UK Medical Research Council Programme Grant (G97 15587) to M.H.J.

- Aguiar, A. & Baillargeon, R. 2002 Developments in young infants' reasoning about occluded objects. *Cogn. Psychol.* **45**, 267–336.
- Baillargeon, R. 1994 Physical reasoning in young infants: seeking explanations for impossible events. *Br. J. Devl Psychol.* **12**, 9–33.
- Baillargeon, R. 2001 Infants' physical knowledge: of acquired expectations and core principles. In *Language, brain, and cognitive development: essays in honor of Jacques Mehler* (ed. E. Dupoux), pp. 341–361. Cambridge, MA: MIT Press.
- Baker, C. I., Keyser, C., Jellema, T., Wicker, B. & Perrett, D. I. 2001 Neuronal representation of disappearing and hidden objects in temporal cortex of the macaque. *Exp. Brain Res.* **140**, 375–381.
- Csibra, G., Davis, G., Spratling, M. W. & Johnson, M. H. 2000 Gamma oscillations and object processing in the infant brain. *Science* **290**, 1582–1585.
- Munakata, Y. 2001 Graded representations in behavioral dissociations. *Trends Cogn. Sci.* **5**, 309–315.
- Piaget, J. 1954 *The construction of reality in the child*. New York: Basic Books.
- Rainer, G. & Miller, E. K. 2000 Effects of visual experience on the representation of objects in the prefrontal cortex. *Neuron* **27**, 179–189.
- Spelke, E. S. 1985 Preferential looking methods as tools for the study of cognition in infancy. In *Measurement of audition and vision in the first year of postnatal life* (ed. G. Gottlieb & N. Krasnegor), pp. 323–363. Norwood, NJ: Ablex.
- Tallon-Baudry, C., Bertrand, O., Perronnet, F. & Pernier, J. J. 1998 Induced gammaband activity during the delay of a visual short-term memory task in humans. *Neuroscience* **18**, 4244–4254.
- Tucker, D. M. 1993 Spatial sampling of head electrical fields: the geodesic sensor net. *Electroenceph. Clin. Neurophysiol.* **87**, 154–163.
- Wynn, K. & Chiang, W. C. 1998 Limits to infants' object knowledge: the case of magical appearance. *W. Psychol. Sci.* **9**, 448–455.