

1 **In press, Proceedings B (as of October 15th 2015)**

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5 **Neural signatures for sustaining object representations attributed to**
6 **others in preverbal human infants**

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8 Short title: Neural bases of ascribed representations

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23 Keywords: infant cognitive development, social cognition, object
24 representation, theory of mind, metarepresentation

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27 Abstract

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29

30 A major feat of social beings is to encode what their conspecifics see, know or
31 believe. While various nonhuman animals show precursors of these abilities,
32 humans perform uniquely sophisticated inferences about other people's
33 mental states. However, it is still unclear how these possibly human-specific
34 capacities develop and whether preverbal infants, similarly to adults form
35 representations of other agents' mental states, specifically
36 metarepresentations. We explored the neuro-cognitive bases of 8-month-olds'
37 ability to encode the world from another person's perspective, using gamma-
38 band EEG activity over the temporal lobes, an established neural signature for
39 sustained object representation after occlusion. We observed such gamma-
40 band activity when an object was occluded from the infants' perspective, as
41 well as when it was occluded only from the other person (Experiment 1), and
42 also when subsequently the object disappeared but the person falsely
43 believed the object to be present (Experiment 2). These findings suggest that
44 the cognitive systems involved in representing the world from infants' own
45 perspective are also recruited for encoding others' beliefs. Such results point
46 to an early developing, powerful apparatus suitable to deal with multiple
47 concurrent representations; and suggest that infants can have a
48 metarepresentational understanding of other minds even before the onset of
49 language.

50

51

52 Humans and other animals encode various aspects of the world,
53 allowing them to successfully navigate their physical and social environment.
54 What possibly sets humans apart from other species is that they attribute
55 mental states to other people as representations of the environment that may
56 be different from their own representations. This ability is usually termed as
57 Theory of Mind and includes reasoning about others' mental states such as
58 beliefs, goals, or desires (1). Theory of Mind capacities seem to emerge early
59 in human development, as a growing body of evidence suggests that infants
60 can interpret others' behaviour with regard to their mental states very early on
61 (2, 3), although the underlying mechanisms are still unclear.

62

63 Already in their first year of life infants can predict others' actions based
64 on their mental states (4), and at around 18 months of age they can also
65 modify their own behaviour accordingly (5, 6, 7). Such findings were taken as
66 evidence that infants attribute beliefs to others and represent these belief
67 contents in the form of metarepresentations (i.e., representations
68 incorporating other representations) (8). Other accounts, however, question
69 the validity of the interpretation of these studies in terms of mental state
70 attributions, and suggest that instead of ascribing mental representations to
71 others, infants simply store object-agent relations (9), form associations, or
72 apply behavioural rules (10). Similar alternatives were also raised with regard
73 to nonhuman animals' Theory of Mind abilities (11). Metarepresentations in
74 general, and Theory of Mind or false belief understanding in particular, have
75 been argued to be absent in other species than humans (12, 13, 14). Thus, to
76 understand the nature and origins of such abilities it would be crucial to

77 assess whether pre-linguistic creatures, specifically human infants attribute
78 representations to other people.

79

80 Different accounts emerged regarding how humans may deal with
81 metarepresentations used in language and in mental state reasoning. Sperber
82 (13) proposed that the most cost-effective way for a cognitive system to
83 handle them would be if *any* representation could also serve as a
84 metarepresentation. Leslie (8), in his work describing a cognitive model of
85 pretense (make-believe play observed in toddlers, such as pretending that a
86 banana is a telephone) argues that in pretense the primary representation of
87 an object is copied into a 'metarepresentational context.' Both of these
88 proposals involve some form of 're-use' of a primary representation. The
89 relation between a linguistic utterance as a primary representation (e.g. 'Dogs
90 can fly') and a corresponding metarepresentation (e.g. 'It is unlikely that *dogs*
91 *can fly*') may seem intuitive. However, it is unclear how such embedded
92 representations are implemented in the cognitive architecture, how they are
93 realized in case of non-linguistic representations, and whether the underlying
94 mechanism could be already present in preverbal infants.

95

96 Earlier research from the domain of action understanding might provide
97 useful insights regarding how the developing cognitive system may deal with
98 representations that regard other people. Specifically, recent
99 electrophysiological findings suggest that infants recruit their motor system
100 (as reflected by decreased sensorimotor alpha-band oscillatory activation) not
101 only when they perform an action but also during the observation and
102 prediction of others' actions (14). In the domain of Theory of Mind,

103 behavioural evidence seems to point to an analogous possibility. When
104 infants or adults are exposed to situations where they can track others'
105 perspective or beliefs, their own representations and the representations
106 attributed to others seem to influence their reactions in analogous ways (3,
107 15). For example, infants show surprise when the outcome of an event does
108 not match another agent's belief about the scene, similarly to their surprise if
109 the outcome contradicts their own knowledge (3). These findings suggest that
110 the two representations may overlap, and are in line with the proposal that a
111 possible mechanism for infants (or adults) to attribute representations to
112 others would utilize their own representational system that is otherwise used
113 for encoding objects and events in the world.

114

115 In the present study we build on this proposal: if infants ascribe a
116 representation to another person, say, about an object, they would rely on
117 their original representation, which would then be used as the content of the
118 mental state. This way infants' own representations of the environment and
119 the representations ascribed to others could be realized through one cognitive
120 system subserving both processes. If so, this enables us to make predictions
121 about the neural signatures of processing ascribed representations. For
122 example, if maintaining a representation of an object, as a primary
123 representation, has a specific neural correlate in infants, we should observe a
124 similar neural activation also if infants process an object representation they
125 attribute to another person. To test these questions, we exploit earlier
126 paradigms that found a specific brain signature accompanying object
127 representations in infants.

128

129 Infants possess powerful representational abilities to sustain the
130 representation of an object even if it is not visible to them anymore. Kaufman
131 and colleagues (16) found increased gamma-band oscillatory activation in
132 electroencephalographic (EEG) responses over the temporal regions when 6-
133 month-old infants witnessed the occlusion of an object, compared to when the
134 object disintegrated before occlusion. Similar activation was found when a
135 hand grasped an occluder behind which an object had previously disappeared
136 (17). Together, these findings suggest that the gamma-band activation
137 signalled that infants actively sustained the representation of the object, which
138 they believed to be behind the occluder. Here we hypothesize that such
139 activation may not only reflect processes involved in how infants handle object
140 representations for themselves, but also signal computations required for
141 attributing a representation about an object to another person.

142

143 In two studies we presented 8-month-old infants with scenes involving
144 an actor and an object, and recorded event-related EEG activity during events
145 involving the occlusion of the object from the infants' or the actor's
146 perspective. An increase in gamma-band activation was predicted when either
147 the infant, or the actor had to sustain the representation of the object.

148

149 **Study 1**

150

151 Study 1 explored 8-month-old infants' understanding of a scene where
152 a person is attending to an object, which is then occluded from her. We asked
153 whether this event triggers an attribution process that involves sustained
154 object representations. In order to test this, we developed scenarios involving

155 occlusion events from multiple perspectives (see Figure 1). First, a target
156 object and an actor were shown on the screen, with the object visible to both
157 the infant and the actor. Then the object was occluded either from only the
158 actor or also from the infant's view. In order to implement a dynamically
159 changing visual access to the object from multiple viewpoints, we placed the
160 object in a box that had two sides removed. By rotating the box either the
161 infant, the actor on the screen, neither, or both could see the object in
162 question. We compared these events to scenarios where the box initially
163 contained an object, but then the object disintegrated while both the actor and
164 the infants could see this event. Therefore the motion of the box was identical
165 in the two kinds of events, but in this latter case the box did not occlude an
166 object from the actor's or infant's view, but rather just empty space.

167

168 On basis of previous findings (16, 17), we predicted increased gamma-
169 band activation during the occlusion of the object from the infants' view.
170 Furthermore, we hypothesized shared underlying mechanisms for sustaining
171 an object representation for the self and for another person. Therefore an
172 increased gamma-band oscillatory activity during Occlusion from Actor would
173 suggest that infants encode that the actor sustains the representation of the
174 object while it is occluded from her. We calculated the average EEG gamma-
175 band activation (25-35 Hz) over the left and right posterior temporal regions
176 specified by earlier studies targeting sustained object representations in
177 infancy (16, 17), during occlusion of the object from the actor's or the infant's
178 view.

179

180

181 **Materials and Methods**

182

183 **Participants.** The final sample consisted of 15 full-term 8-month-old infants
184 (mean age = 246.3 d; age range 236-255 d).

185

186 **Stimuli.** Two types of videos were used (corresponding to the two conditions).

187 Both featured a female actor who looked at a rotating box open at two sides
188 that contained an object. First, the opening of the box was facing away for 200

189 ms, then it rotated to reveal the object in 600 ms, and stood still for 200 ms.

190 Then the Actor turned to the object for 600 ms. This was followed by the

191 object remaining present (Object Present – Occlusion condition, video S1) or

192 the object disintegrating in 600 ms (Object Absent – Occlusion condition,

193 video S2). Following a 300-500 ms (randomized length) still period, the box

194 turned further, occluding the object (Object Present – Occlusion condition) or

195 an empty area (Object Absent – Occlusion condition) from the Actor in 600

196 ms. After a 700-900 ms (randomized length) still period, the box rotated again

197 further and occluded the object (Object Present – Occlusion condition) or an

198 empty area (Object Absent – Occlusion condition) from the Infant as well. The

199 trial ended with an 800 ms still period with the box completely turned away

200 (identical in the two conditions). For further details regarding stimuli and

201 procedure see *SI Materials and Methods*.

202

203 **EEG recording and analysis.** Continuous EEG was recorded using Hydrocel

204 Geodesic Sensor Nets (Electrical Geodesics Inc., Eugene, OR, USA) from

205 124 channels equally distributed on the scalp, referenced to the vertex (Cz).

206 The ground electrode was at the rear of the head (between Cz and Pz). The

207 sampling rate was 500 Hz with a low-pass filter of 200 Hz. The EEG was
208 segmented into two types of segments of interest.

209

210 The first segment (Occlusion from Actor) was the part of the video
211 when, in the Object Present condition, the object was gradually hidden from
212 the actor due to the rotation of the box, while the infants still saw it. In the
213 Object Absent condition this segment included the identical movement of the
214 empty box. This segment was time-locked to the start of the movement of the
215 box, and lasted 1200 ms after rotation onset, of which the rotation took place
216 in the first 600 ms. The baseline period for the Occlusion from Actor segment
217 was the 200 ms recording preceding the rotation of the occluder. The second
218 segment of interest (Occlusion from Infant) corresponded to the period when
219 the object became gradually hidden from the infants. This segment was time-
220 locked to the start of the respective movement of the occluder and had a
221 length of 1200 ms. In the Occlusion from Infant segment we used an epoch
222 that roughly matched (due a jittered period after the Occlusion from Actor
223 segment) the baseline period in the first segment: a 200-ms-long interval
224 ending 1500 ms before the onset of Occlusion from Infant (for calculating this
225 baseline period see *SI Materials and Methods*).

226

227 The EEG data were examined and segments were excluded if they
228 were judged as not attended by the infant based on the video recording, or
229 contained artefacts as judged by the automatic or manual artefact detection
230 (for further details see *SI Materials and Methods*). After the time-frequency
231 transformation performed on the cleaned data, we compared oscillatory
232 activity between the two conditions over 5-5 channels in right (channels 97,

233 98, 102, 103, 109, positioned above channel T3 in the 10-20 system) and left
234 (channels 40, 41, 46, 47, 51, above channel T4 in the 10-20 system) temporal
235 areas. Electrode sites were selected based on previous work by Kaufman and
236 colleagues (16, 17). We analysed the lower frequencies (25-35 Hz) of the
237 gamma range, where activation was the most pronounced in earlier studies,
238 (17) for our events of interest.

239

240 [Figure 1 about here]

241

242

243 **Results**

244

245 First we analysed gamma-band oscillatory activation in the two
246 segments separately, in two-way ANOVAs with Condition (Object Present -
247 Occlusion vs. Object Absent - Occlusion) and Hemisphere (Left vs. Right) as
248 within-subjects factors. To assess whether our results replicate earlier findings
249 on neural signatures of sustained object representations, we analysed
250 activation during the Occlusion from Infant segment (Segment 2). Analysis
251 revealed a significant main effect of Condition, $F(1,14) = 13.23$, $p = .003$,
252 $partial \eta^2 = .49$, due to significantly higher activation in the Occlusion ($M = 0.09$
253 μV , $SE = .03$), compared to Object Absent - Occlusion condition ($M = -0.07$
254 μV , $SE = .04 \mu V$, Figure 2B). There was no main effect of Hemisphere, and
255 no interaction between Condition and Hemisphere ($F(1,14) = 0.04$, $p = .81$;
256 and $F(1,14) = 0.06$, $p = .86$).

257

258 We conducted a similar two-way ANOVA for the Occlusion from Actor
259 segment (Segment 1), which revealed a significant interaction between
260 Condition and Hemisphere ($F(1,14) = 4.99, p = .04, \text{partial } \eta^2 = .26$), and a
261 marginally significant main effect of Condition ($F(1,14) = 4.53, p = .052, \text{partial}$
262 $\eta^2 = .24$). There was no effect of Hemisphere ($F(1,14) = 0.06, p = .81$). To
263 understand the interaction, we performed separate t-tests for the two
264 hemispheres. There was no significant difference between Occlusion and
265 Control in the right hemisphere, $t(14) = -1.03, p = .32$. Importantly, there was a
266 significant difference in the left hemisphere, $t(14) = -2.56, p = .023, r^2 = .32$,
267 due to higher gamma activation in the Object Present - Occlusion condition (M
268 $= 0.08 \mu\text{V}, SE = 0.05 \mu\text{V}$) than in Object Absent - Occlusion condition ($M = -$
269 $0.12 \mu\text{V}, SE = 0.04 \mu\text{V}$, see Figure 2A).

270

271 [Figure 2 about here]

272

273

274 To assess whether the pattern of activation in the two segments was
275 similar to each other, we analysed them together in a repeated measure
276 ANOVA with Segment (Occlusion from Actor vs. Occlusion from Infant),
277 Condition (Object Present - Occlusion vs. Object Absent - Occlusion) and
278 Hemisphere (Left vs. Right) as within-subjects factors. We found a significant
279 main effect of Condition, $F(1,14) = 13.24, p = .003, \text{partial } \eta^2 = .49$. No other
280 main effect or interaction was significant (for mean values in Study 1, see
281 Figure 3A). Thus, while in the Occlusion from Actor segment the effect was
282 more pronounced on the left side, the direction of activation in this segment

283 was similar in the two hemispheres and together they did not differ
284 significantly from that in the Occlusion from Infant segment.

285

286 [Figure 3 about here]

287

288 In addition to analysing activation in our predicted time windows, we
289 observed a further activation within the same frequency range in the
290 Occlusion from Actor segment for the 1000-1100 ms period (see Figure 2A).
291 When we analysed activation this additional time window, we found a
292 marginally significant effect of Condition in the left hemisphere ($t(14) = -2.07$, p
293 $= .057$, $r^2 = .23$) with higher activation in the Object Present - Occlusion
294 condition than in the Object Absent - Occlusion condition ($M = 0.09 \mu\text{V}$, $SE =$
295 $.05 \mu\text{V}$, and $M = -0.11 \mu\text{V}$, $SE = .07 \mu\text{V}$, respectively). A similar analysis did
296 not yield any significant effects in the right hemisphere and in the Occlusion
297 from Infant segment. While this late activation burst in Occlusion from Actor
298 segment may signal a possible difference between processing
299 representations attributed to another agent and first person representations, it
300 was not predicted. We intended to confirm this finding in Study 2.

301

302 **Discussion**

303

304 Our results from the Occlusion from Infant segment are in line with
305 earlier evidence pointing to a signature of infants' sustained object
306 representation (16, 17). Specifically, we observed higher gamma-band
307 activation over posterior temporal areas when an object became occluded
308 from the infants compared to when there was no object present. Crucially, we

309 observed similar activation when the object became occluded from the actor
310 only (Occlusion from Actor). Note that in the Occlusion from Actor segment
311 the object was still visible to infants, therefore they did not have to sustain the
312 object representation from their own perspective. This suggests that infants
313 attributed a sustained representation of the object to the actor when she lost
314 visual access to the object.

315

316 These results suggest that 8-month-old infants successfully computed
317 the visual perspective of the actor regarding the object, an ability that is rarely
318 observed at such a young age. Furthermore, while visual perspective taking
319 (computing whether an agent can see an object) is necessary, it may not be
320 sufficient to explain our findings. Taking the gamma-band oscillatory activity at
321 the time of occlusion as an indicator of sustained object representation,
322 infants in our study did not only infer that the person no longer saw the object
323 (as this would apply in the Object Absent - Occlusion condition as well); they
324 also attributed to her the representation of the continued existence of the
325 object behind the occluder.

326

327 Identifying the mechanisms at play when infants attribute a sustained
328 object representation (a *true* belief) to another person allows further
329 investigations of belief attribution processes. If the activation found in Study 1
330 accompanies events involving attributed object representations, then it should
331 be present regardless of the veridicality of this representation, i.e., even when
332 the other person holds a *false* belief regarding the object's existence behind
333 the occluder.

334

335 **Study 2**

336

337 We developed a false belief scenario similar to the events in Study 1
338 (see SI Figure 1). Eight-month-old infants were presented with the same initial
339 event in which the actor attended to an object. Then in the critical condition
340 the object became occluded from the person (Segment 1 – identical to
341 Segment 1 Study 1), and afterwards the object disintegrated (Segment 2).
342 This disintegration was therefore visible to the infants but not to the actor;
343 hence this event must have resulted in the actor's false belief that the object
344 was still behind the occluder. The critical question was whether infants would
345 encode that the representation of the object cannot be discarded on behalf of
346 the actor but it must be further sustained. Such an attribution process might
347 be indicated by gamma-band activation during the disintegration event that is
348 seen only by the infant but not the actor.

349

350

351 **Materials and Methods**

352

353 **Participants.** The final sample consisted of 15 full-term 8-month-old infants
354 (mean age = 245 d; range = 229-261 d).

355

356 **Stimuli.** In Study 2, the setting of the scenes and the initial part of the videos
357 (including the first segment of interest) was identical to Study 1. Then in the
358 Object occluded – False Belief condition the object was occluded from the
359 actor by the rotating box in 600 ms (Occlusion from Actor) and after a still
360 period of 600 ms it disintegrated during 600 ms, while only the infants and not

361 the actor could see this event (Video S3). We will refer to this disintegration
362 period as False Belief event because in this case infants could note that the
363 object ceased to exist and is not present anymore, and could infer that the
364 actor should falsely believe it still to be present behind the occluding side of
365 the box. In the Object Absent – True Belief condition (Video S4) the object
366 disintegrated when the actor still saw the object, and subsequently the empty
367 space was occluded in 600 ms. Following a 600 ms still period, (during the
368 corresponding disintegration period of the Object Occluded – False Belief
369 condition) in the Object Absent – True Belief condition the empty box
370 remained turned away from the Actor for 600 ms. Thus, the two conditions
371 differed only in the timing of the disintegration of the object: after (False Belief)
372 or before (True Belief) it was occluded from the actor. Finally, in both
373 conditions the empty box rotated back towards the actor. Hence, infants in
374 Study 2 never saw the object being occluded from them. The rotation of the
375 box was identical in the two conditions. For further details regarding stimuli
376 and procedure see *SI Materials and Methods*.

377

378 **EEG recording and analysis.** Except for segmentation, EEG recording and
379 analysis was identical to that of Study 1. Similarly to Study 1, the first segment
380 (Occlusion from Actor) was the part of the video when the object was
381 gradually hidden from the actor by the rotation of the box (in the Object
382 Occluded – False Belief condition), while the infants still saw it; or the identical
383 movement of the empty box (in the Object Absent – True Belief Condition).
384 Hence, in the Occlusion from Actor segment, we specified the same time
385 window of interest as in Study 1, and the baseline was again a 200-ms-long
386 epoch finishing 1200 ms before the start of the segment.

387

388 The second segment of interest (False Belief Event) in Study 2
389 corresponded to the period when the object disintegrated after being occluded
390 from the person (or the same time period during the Object Absent – True
391 Belief Condition) and the subsequent still image. This period lasted 800 ms
392 and its start was time locked to the start of disintegration event. Similarly to
393 Study 1, the baseline was a 200-ms-long epoch finishing 1200 ms before the
394 start of the segment (the same baseline as for Occlusion from Actor). In this
395 False Belief segment, we analysed activation throughout the disintegration
396 event, from 1200 to 1800 ms, where 1200 ms corresponded to the onset of
397 the disintegration and 1800 ms to the time point when the object had fully
398 disappeared.

399

400

401 **Results**

402

403 We calculated the average gamma-band activation (25-35 Hz) the
404 same way as in Study 1 during two Segments of interest: Occlusion from
405 Actor and False Belief.

406

407 As direct comparison between the two segments was not meaningful
408 (one being an occlusion, which can be seen as a discrete event, while the
409 other is a disintegration with a gradual temporal unfolding), activations in the
410 two segments were analysed separately. A two-way ANOVA on the Occlusion
411 from Actor segment with Condition (Object Occluded – False Belief vs. Object
412 Absent – True Belief) and Hemisphere (Left vs. Right) as within-subjects

413 factors revealed a main effect of Condition ($F(1,14) = 5.98, p = .03, \text{partial } \eta^2 =$
414 $.3$). This effect was due to higher activation in the Object Occluded – False
415 Belief condition ($M = 0.044 \mu\text{V}$) than in Object Absent – True Belief ($M = -0.07$
416 μV , Figure 3B). No other main effect or interaction emerged.

417

418 We then compared activation during Occlusion from Actor in Study 2 to
419 that of Study 1. These segments were identical in the two studies and both
420 depicted an Occlusion from Actor event. A three-way mixed ANOVA was
421 conducted with Condition (Object Present vs. Object Absent) and Hemisphere
422 (Left vs. Right) as within-subjects factors and Study (1 vs. 2) as a between-
423 subjects factor. This analysis revealed a main effect of Condition ($F(1,28) =$
424 $10.13, p = .004, \text{partial } \eta^2 = .27$), which was due to higher activation in the
425 Object Present condition ($M = 0.05 \mu\text{V}, SE = 0.03 \mu\text{V}$) than in Object Absent
426 condition ($M = -0.07 \mu\text{V}, SE = 0.02 \mu\text{V}$). There was no effect of Study ($F(1,14)$
427 $= 0.01, p = .92$), and no interaction.

428

429 Next we entered the activation during the False Belief segment of
430 Study 2 in a two-way ANOVA with Condition (Object Occluded – False Belief
431 vs. Object Absent – True Belief) and Hemisphere (Left vs. Right) as within-
432 subjects factors. There was a significant main effect of Condition, $F(1,14) =$
433 $8.47, p = .01, \text{partial } \eta^2 = .38$, due to significantly higher activation in the
434 Object Occluded – False Belief ($M = 0.07 \mu\text{V}, SE = 0.04 \mu\text{V}$), compared to
435 Object Absent – True Belief condition ($M = -0.01 \mu\text{V}, SE = 0.05 \mu\text{V}$, Figure 4).
436 There was no main effect of Hemisphere, and no interaction.

437

438

439

440 [Figure 4 about here]

441

442

443 Finally, we analysed the late burst activation in the Occlusion from
444 Actor segment in the left hemisphere to test whether our findings from Study 1
445 were replicated. We analysed activation from the two studies with Condition
446 (Object Present vs. Object Absent) as within-subjects factor and Study (1 vs.
447 2) as between-subjects factors. There was a significant main effect of
448 Condition ($F(1,28) = 7.97, p = .01, \text{partial } \eta^2 = .22$), due to higher activation in
449 the Object Present ($M = 0.07 \mu\text{V}, SE = .03 \mu\text{V}$), than in Object Absent
450 condition ($M = -0.09 \mu\text{V}, SE = .04 \mu\text{V}$), and no main effect of Study (for
451 detailed analysis in this late activation see *SI Additional Analyses*).

452

453 **Discussion**

454

455 The results of Study 2 are consistent with the proposal that infants
456 ascribe object representations to others not only when they attribute true
457 beliefs, but also when they can attribute false beliefs to them. Similarly to
458 Study 1, belief attribution here was based on visual perspective taking (infants
459 had to encode that the object was not visible to the person). Crucially, in the
460 False Belief segment, when the object disintegrated and this was visible to the
461 infant but not to the person, there was increased gamma-band activation,
462 similarly to the occlusion events (occlusion from the infant or from the person).

463

464 These results suggest that infants encode that the other person
465 continues to represent the object, despite evidence that prompts them to
466 discard their own representation of the very same object. Since disintegration
467 has been previously shown not to trigger sustained object representation (16),
468 higher gamma activation during this event reflects that the infants sustained
469 the object representation they had attributed to the actor (who falsely believed
470 the object to be behind the occluder), even though this representation was in
471 sharp conflict with the infants' own perception (as the object disintegrated).
472 Thus, the infants must have encoded that the other person had seen the
473 object being occluded, but did not see the disintegration, and hence the
474 attributed object representation could not be discarded on her behalf, but had
475 to be possibly refreshed and sustained further.

476

477 We see no obvious ways to explain the activation patterns we
478 observed in Study 1 and 2 in terms of simpler cognitive mechanisms that do
479 not involve belief attributions. First, activation during occlusion from the actor
480 only (Occlusion from Actor segments in both studies) could not be due to
481 infants' own sustained representation, since they continued to see the object
482 during this event. Second, our results cannot be attributed to perceptual
483 differences between the conditions (e.g., that the object was present in one
484 condition but not in the other), since we subtracted the corresponding
485 baseline activation from our data where this difference already existed, hence
486 any activation difference due to this factor would have been thus subtracted
487 from the time window of interest. Furthermore, results from the Occlusion from
488 Actor segment in Study 2 excluded the possibility that the gamma-band
489 activation in the Occlusion from Actor segment was due to infants' expectation

490 of occlusion from their own perspective, as no such occlusion followed.

491

492 Additionally, results from Study 2 confirm the late burst activation we
493 found in Study 1. This additional burst of activation therefore was present in
494 both studies towards the end of the Occlusion from Actor segment. During this
495 period that followed after the occlusion of the object from the actor, nothing
496 was happening in the video. Therefore this activation likely reflects
497 computational processes that involve further processing of the earlier
498 observed events, possibly related to keeping in mind the object representation
499 attributed to the actor.

500

501

502 **General Discussion**

503

504 The goal of the present paper was to investigate whether young infants
505 ascribe representations to others during tracking of what this other person
506 sees, knows or believes, through utilizing their own representational system
507 that is otherwise used for encoding objects and events in the world. In Study 1
508 we presented infants with scenes depicting a simple situation involving an
509 object and actor, and events where the infant's or the other person's
510 perceptual access to the object changed dynamically. In Study 2 we
511 constructed a case where this event could lead to a false belief about the
512 presence of the object in the other person. We recorded event-related
513 oscillatory activity during the observation of these events.

514

515 Earlier studies (16, 17) found gamma-band oscillatory activity in infants
516 for sustained object representation. We found similar gamma-band activations
517 when an object became occluded from the infants' own (Study 1, Occlusion
518 from Infant) or someone else's perspective (Study 1 & 2, Occlusion from
519 Actor), consistent with the possibility that there are shared underlying
520 mechanisms for sustained object representations for the self and for the ones
521 attributed to another person. Crucially, the activation found in response to
522 object occlusion from the other person's perspective could only be explained
523 by the enrolment of an object representation ascribed to her. This is
524 supported by the fact that during this interval infants continued to perceive the
525 object and therefore did not need to sustain the representation for them.
526 Importantly, the same activation was observed in a false belief situation
527 where, after being occluded from the actor, the infant saw the object
528 disintegrating (Study 2, False Belief segment). Due to disintegration the object
529 ceased to exist from the infant's point of view, therefore EEG activation during
530 this event is likely due to a sustained object representation on behalf of the
531 actor. Together, the activations we found are indicative of the on-line
532 processing of a representation that infants attribute to another person – a
533 metarepresentation - based on her earlier perceptual access.

534

535 While here we investigated one kind of belief content (beliefs about the
536 presence of objects), based on an approach arguing for shared mechanisms
537 for infants' own representations and for attributed belief representations other
538 kinds of belief contents should also activate the corresponding cognitive
539 systems in the observer's mind and be involved in operations on the ascribed
540 belief representations. Recent evidence suggests that adults show an

541 increased N400 effect when they can infer that another person will have
542 difficulties to integrate a sentence due to a semantically incongruous word
543 (semantic violation) while they don't perceive it as semantic violation, similarly
544 to the cases when only they themselves perceive a semantic violation (18).

545

546 These findings raise the question how infant's primary representations
547 would be separated from the representations ascribed to others. While the
548 present study does not directly address this question, we observed an
549 additional burst of activation that accompanied only processing the object
550 occlusion from the actor's perspective, in both studies. The fact that similar
551 activation did not occur during the Occlusion from the Infant events suggests
552 that it might reflect some further processing of ascribed representations, and
553 could potentially play a role in distinguishing an ascribed representation from
554 the infants' own reality representation.

555

556 The finding that the cognitive systems that are otherwise dedicated for
557 representing objects are also involved in mentalizing processes points to the
558 possibility that infants recruit cognitive systems from outside of a
559 hypothesised ToM-network (19) or ToM module (20) when representing
560 others' beliefs. Yet, we do not take such data to speak to the question that
561 has repeatedly emerged with regard to ToM capacities, namely, whether such
562 reasoning is predominantly subserved by domain-general or domain-specific
563 processes (21). The gamma activations found in the 'Occlusion from Actor'
564 events most likely signal sustaining an attributed representation of an object.
565 This process relates to the encoding of the *content* of the actor's belief, in
566 other terms to the formation of a metarepresentation of this belief content.

567 However, as this is likely one of the first steps in the process of belief
568 ascription (22), our findings leave open the possibility that in the further steps
569 of belief processing such representations would serve as input to more
570 specialized mindreading processes.

571

572 Metarepresentations involving mental states were argued to differ from
573 other kinds of metarepresentations, for instance from those of public
574 representations (such as utterances) or abstract representations, and there
575 could be separate metarepresentational competencies for each, as a distinct
576 evolved adaptation (13). In line with this, behavioural evidence suggests that
577 adults process belief representations distinctly from other meta-
578 representations that are not representations of mental states (such as
579 vignettes describing an event) (23).

580

581 Together, our studies demonstrate that preverbal infants engage in
582 encoding the visual perspective and the false belief of others. By possessing
583 such powerful representational capacities infants are endowed with the ability
584 to ascribe to others any representations they themselves can form, including
585 representations that are in conflict with their own representation of reality. One
586 might wonder whether these capacities are innate or are subject to change
587 during development. While this is a question for future studies, it is possible
588 that some basic ToM mechanisms have an innate basis, although they likely
589 require some critical social experience.

590

591 Representing beliefs through forming metarepresentations of ascribed
592 representations seems possible before the onset of language. The fact that

593 language might not be necessary to form metarepresentations in belief
594 reasoning raises the possibility that similar cognitive processes could be
595 present in non-human animals. By the logic that cognitive systems
596 responsible to represent the physical world might be “re-used” to represent
597 others’ mental state contents, the question emerges whether non-human
598 animals could in some situations metarepresent their conspecifics’
599 representations. However, in the absence of empirical evidence this question
600 remains a task for future research.

601

602 Ethics Statement

603

604 All infants were recruited through a local database and parents signed an
605 informed consent prior to participation. All studies received full ethical
606 approval from the United Ethical Review Committee for Research in
607 Psychology (EPKEB) in Hungary and were conducted according to the
608 principles of the Declaration of Helsinki.

609

610 Data accessibility

611 For the time-frequency transformations we used EEGLAB, an open source
612 toolbox for MATLAB[®] (<http://www.mathworks.com/products/matlab/>) available
613 at: <http://sccn.ucsd.edu/eeglab/>; and the custom-made script collection
614 WTools (available at request). EEG dataset is available at
615 <http://datadryad.org/review?doi=doi:10.5061/dryad.r5p6q>.

616

617 Author contributions

618 D.K., Á.M.K., E.P. and G.C. designed research; D.K. performed research;
619 D.K. and E.P. analysed data; and D.K., Á.M.K., E.P. and G.C. wrote the
620 paper. The authors declare no conflict of interest.

621

622

623 Acknowledgements

624 We thank the families who participated in this study, and members of the
625 Cognitive Development Center of Central European University and Dan
626 Sperber for valuable comments on previous versions of the manuscript.

627

628 Funding

629 This research was supported by the European Research Council under the
630 European Union's Seventh Framework Programme (FP7/2007-2013)/ERC
631 starting grant to Á.M.K. (284236- REPCOLLAB) and a European Research
632 Council Advanced Investigator Grant (OSTREFCOM) to G.C. Eugenio Parise
633 is a Lecturer in the International Centre for Language and Communicative
634 Development (LuCiD) at Lancaster University. The support of the Economic
635 and Social Research Council [ES/L008955/1] is gratefully acknowledged.

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703

704 **Figure legends**

705

706 **Figure 1.** Schematic illustrations of the events in Study 1. The first 1.5
707 seconds of each video were identical in the two conditions (A). In the Object
708 Present – Occlusion condition the object remained present, and was occluded
709 by the rotating box, first from the actor’s point of view, then from the infant as
710 well (B). In the Object Absent – Occlusion condition the rotation of the box
711 was identical but occluded an empty area from the actor’s and then the
712 infant’s side (C). In both conditions the trial ended with the box completely
713 turned away.

714

715 **Figure 2.** Time-frequency difference plots depicting average gamma-band
716 oscillatory activation over the left and right posterior temporal cortex during
717 the two segments in Study 1. Plots reflect mean activation difference between
718 conditions; positive difference indicates higher activation in Object Present -
719 Occlusion condition than in Object Absent - Occlusion condition. In both
720 segments, 0 ms marks the onset of the occlusion event; in the first segment
721 (A) from the Actor, in the second segment (B) from the Infant. Red rectangles
722 indicate the time and frequency range over which statistics were computed.

723

724 **Figure 3.** Mean activation in (A) Study 1 during Occlusion from Actor and
725 Occlusion from Infant, and (B) Study 2 Occlusion from Actor at the target time
726 windows (550-650 ms), at five left (L) and five right (R) temporal electrodes,
727 over the 25-35 Hz frequency range. Error bars represent standard errors.

728

729 **Figure 4.** Time-frequency analysis of the average EEG during the False Belief
730 event at ten electrodes over the left and right temporal cortex in Study 2. The
731 plot reflects mean activation difference between conditions; positive difference
732 indicates higher activation in Object Occluded – False Belief condition than in
733 Object Absent – True Belief. 1200 ms is the onset of the disintegration event
734 and 1800 is the offset. Red rectangle indicates the time and frequency range
735 over which statistics were computed.

736