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1 **Title**

2 Social reward anticipation in infants as revealed by event-related potentials

3

4 **Abbreviated title**

5 Social reward anticipation in infants

6

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17

18 **Abstract**

19 Infants engage in gaze interaction from the early stage of life. Emerging
20 studies suggest that infants may expect social reward of shared attention
21 before looking to the same object with another person. However, it was
22 unknown about the neural responses during the anticipation of social
23 rewards before shared attention in infants. We tested infants' reward
24 anticipations in the gaze cueing situation measured by event-related
25 potentials in the social association learning task. Six- to ten-month-old
26 infants (N=20) repeatedly observed that a female predictively looked toward
27 the animation position (valid condition) or another female looking away
28 from the animation (invalid condition). It was posited that infants could
29 learn associations between female faces and the event of shared attention.
30 The results showed that the stimulus preceding negativity which reflects
31 reward anticipation before the animation presentation was elicited in the
32 second half of the learning phases in the valid condition. Additionally, after
33 the presentation of the face, N290 was greater in the second half of the
34 learning phase than in the first half in the valid condition. These results
35 suggest that infants can anticipate social reward from gaze cues, and
36 learning the gaze cueing validity may affect not only reward anticipation

37 but face perception.

38

39 **Keywords:** reward anticipation, ERP, infant, gaze cueing

40

41 **Introduction**

42 Over the years, it has been argued that social situations are intrinsically
43 rewarding for human infants from a very early stage of life (Tomasello,
44 Carpenter, Call, Behne, & Moll, 2005). Many precursors of social bias have
45 been observed in newborn babies, for example, newborns preferentially look
46 for face-like stimuli (Johnson, Dziurawiec, Ellis, & Morton, 1991).

47 Additionally, from the time of being newborns, infants are sensitive to
48 others' direction of gaze. Studies have indicated that newborns discriminate
49 between direct and averted gazes, and they were faster to make saccades to
50 peripheral targets cued by gaze direction (Farroni, Massaccesi, Pividori, &
51 Johnson, 2004). These initial biases to others' faces and gaze direction lead
52 infants to engage in gaze interaction from the early stage of life (Tomasello,
53 1995; Tomasello et al., 2005).

54 Because infants' attentional orientation is influenced by gaze only shifts
55 (Farroni et al., 2004), gaze cueing without head orientation has been used to
56 investigate how infants' cognitive processing is modulated by other's gaze
57 direction. We define gaze cueing situations as one in which visuospatial
58 attentional shifts are triggered by another individual's gaze direction. Reid,
59 Striano, Kaufman, & Johnson (2004) measured event-related potentials
60 (ERPs) in 4-month-old infants while watching gaze cueing situations and
61 found enhanced slow-wave responses to uncued objects when compared to
62 cued objects. A behavioural study also revealed that 4-month-old infants
63 looked less at the cued object than at the uncued object when the objects
64 were presented simultaneously after repeatedly observing gaze-cueing
65 situations (Reid & Striano, 2005). It was suggested that the uncued object
66 was perceived as more novel than the object previously cued by the adult's
67 gaze, and gaze cueing may facilitate object information processing. Hoehl,
68 Reid, Mooney, & Striano (2008) examined the attentional process during the
69 gaze cueing situation in four-month-olds, measuring the mid-latency
70 negative component (Nc). They found the shorter latency of Nc to the cueing
71 situation when compared to the uncueing situation, suggesting that gaze
72 cueing induced faster and more efficient processing of the target

73 object. From four months of age, there is no difference between gaze only
74 cueing and cueing with head orientation in facilitative effects on object
75 information processing indexed by ERPs and looking behaviour (Hoehl,
76 Wahl, & Pauen, 2014). These studies suggest that gaze only cueing
77 facilitates cognitive processing in infants.

78 Gaze cueing effects on cognitive processing can be modulated by facial
79 information. Hoehl & Striano (2010) showed an enhanced Nc for objects that
80 had been gaze-cued by a fearful compared to a neutral face in six-month-
81 olds. Another study demonstrated that an enhanced slow-wave response at
82 four months of age was found for objects that were cued by the stranger's
83 gaze compared to objects that were cued by caregiver's eye gaze, suggesting
84 facial familiarity modulates gaze cueing effects (Hoehl, Wahl, Michel, &
85 Striano, 2012). More recently, Jessen & Grosmann (2020) examined the
86 impact of facial trustworthiness on object processing in gaze cueing
87 situations. They reported that uncued objects elicited a larger Nc when the
88 gaze cue was provided by trustworthy compared to untrustworthy faces.
89 Previous studies have shown how perceptual information of gaze cueing
90 modulates cueing effects on cognitive processing in infants.

91 A remaining question is why gaze cueing facilitates cognitive processing
92 in infants. It has been theoretically suggested that infants follow other's
93 gaze direction because sharing interest and attention in the same
94 object/event is rewarding to them (Moore & Corkum, 1994; Tomasello, 2007).
95 Shared attention is defined as the situation when two individuals are
96 looking to the same object/event (Fiebich & Gallagher, 2012). Thus, infants'
97 gaze following behaviour toward objects in gaze cueing situations can be
98 defined as shared attention. Some behavioural studies have shown
99 empirical results supporting the notion that shared attention is rewarding
100 for infants and thus gaze cueing modulates cognitive processing. For
101 example, Ishikawa, Yoshimura, Sato, & Itakura (2019) revealed that
102 observations of gaze cueing situations enhance reaching preference for the
103 cued object and cueing face in ten-month-olds. With repeated observations of
104 gaze cueing situations, it is considered that infants can learn the association
105 among the cued object, cueing face, and the reward of shared attention. In
106 this paper, we refer to the reward which can be obtained in social interactive
107 situations as a social reward. Thus, the social reward can include another's
108 smiling, speech, contingent responses and shared attention. It has been

109 shown that reward value transfers to the cue associated with the social
110 reward through association learning in infants (Tummeltshammer,
111 Feldman, & Amso, 2019). Thus, in Ishikawa et al. (2019), the preferences
112 are modulated because the object and face are associated with the social
113 rewarding event of shared attention. Another developmental study
114 measured nine-month-old infants' heart rates before executing gaze
115 following behaviour toward an object (Ishikawa & Itakura, 2019); their
116 heart rates increased from the baseline before they followed the adult's
117 direction of gaze, suggesting that infants may expect reward before shared
118 attention. It has been suggested that social reward expectation can be
119 reflected in physiological arousal (Critchley et al., 2005; Tummeltshanmer et
120 al., 2019). However, because general arousal can affect cognitive processing
121 and behavioural responses to stimuli (see a review in Aston-Jones,
122 Rajkowski, & Cohen, 1999), Ishikawa & Itakura (2019) mentioned a
123 possibility that infants showed gaze following because of merely enhanced
124 arousal rather than social reward expectation. Thus, neural activations
125 should be measured to examine whether infants anticipate the social reward
126 of shared attention with another person. The neural processing of infants'
127 social reward anticipations is little known because the methodology to
128 measure looking behaviour and physiological responses is limited. Although
129 it has been shown that physiological responses correlate with brain
130 activities in the reward system during monetary reward anticipation
131 (Schneider, Leuchs, Czisch, Sämann, & Spormaker, 2018), infants' brain
132 activations during anticipations of social rewards have not been tested. It is
133 necessary to measure brain responses during the anticipation of social
134 rewards before shared attention in infants.

135 In this study, we used an associative learning task based on gaze cueing
136 situations and measured infants' ERPs to test whether they anticipate social
137 rewards before shared attention. Infants repeatedly observed that a female
138 face provided gaze cueing toward the animation position (valid condition) or
139 another female face gazing away from the animation (invalid condition). It
140 was posited that infants learn associations between female faces and the
141 reliability of gaze cueing toward the animation position, leading to the social
142 reward of shared attention. The stimulus preceding negativity (SPN) is a
143 component that reflects the anticipation of a stimulus or feedback especially
144 with monetary reward in adults (Brunia, Hackley, van Boxtel, Kotani, &

145 Ohgami, 2011; Kotani et al., 2009). Furthermore, many studies suggest that
146 the SPN is related to general reward anticipations in
147 reinforcement/associative learning (Masaki, Yamazaki, & Hackley, 2010;
148 Foti & Hajcak, 2012; Morís, Luque, & Rodriguez-Fornells, 2013). This
149 component is elicited mostly in the anterior regions of the scalp at least
150 after 700 ms from the visual cue of the reward (Mnatsakanian & Tarkka,
151 2002; Walentowska et al., 2018). An adult study examining the time-course
152 of the SPN has shown that the amplitude of the SPN is the highest just
153 before the presentation of monetary reward (Wang, Li, Nie, & Zheng, 2020),
154 and the SPN has been defined as the mean voltage within 200 ms prior to
155 the reward (see a review in Glazer et al., 2018). In a recent developmental
156 study, Engle et al. (2021) has measured ERPs during a passive associative
157 learning paradigm with social and non-social stimuli. In this previous study,
158 preschool children passively observed the sequence of stimuli and learned
159 associations between visual cues and target stimuli (smiling face or toy).
160 The SPN has been found in three- to four-year-old children within 200 ms
161 prior to the onset of the target and the amplitude was larger for social than
162 non-social stimuli (Engle et al., 2021). To our knowledge, the youngest age in
163 which the SPN can be observed was this age group around three-years-old,
164 however, some physiological studies have shown that infants less than 1-
165 year-old can anticipate social rewards. For example, Tummeltshanmer et al.
166 (2019) reported that seven-month-old infants can learn associations between
167 cues (arbitrary shapes) and social rewards (smiling mother's face), and they
168 can anticipate the rewards while watching cues indexed by pupil dilations.
169 Thus, after infants learned the validity of gaze cueing (i.e., whether gaze
170 cues are predictive of the target object), the SPN would be observed before
171 the animation with a valid gaze cue in infants around seven months old.

172 We also hypothesized that learning the validity of gaze cueing would
173 affect the perception of the face associated with the social reward of shared
174 attention. Because a previous study revealed that the observations of gaze
175 cueing situations enhanced facial preference (Ishikawa et al., 2019), ERP
176 components of face perceptions would be modulated by learning. The N290
177 and P400 have been broadly used as components that reflect infants' face
178 perception (Conte, Richards, Guy, Xie, & Roberts, 2020; De Haan, Johnson,
179 & Halit, 2003). The N290 can reflect infants' face processing, which is
180 accelerated by the repetition of an identical face (Peykarjou, Pauen, &

181 Hoehl, 2016). Thus, knowledge of faces learned through repetitive
182 presentations of gaze cueing situations would modulate the N290.
183 Additionally, the literature reveals that the trustworthiness of faces
184 modulates the P400 amplitude (Jessen & Grossmann, 2016). These
185 components may reflect preferences for faces in infants. If infants learn the
186 validity of gaze cueing for each face, the N290 and P400 would be modulated
187 after learning.

188 This study aimed to investigate neural responses during social reward
189 anticipation in early infancy by examining the SPN before the situation of
190 shared attention. We also tested the effects of associative learning between
191 face and gaze validity on face perception, measured by the N290 and P400.
192 We hypothesised that the amplitudes of the SPN, N290 and P400 are
193 enhanced in the valid condition after learning the gaze validity.

194

195 **Method**

196 The final sample for analysis consisted of 20 six- to ten-month-old infants
197 (9 female, 11 male) who participated throughout the study duration. The
198 mean age of the infants was 229.7 days old (range, 180–307 days old). Four
199 additional infants were tested but excluded from the analysis sample
200 because of an insufficient number of trials. Due to refusal to wear the EEG
201 cap, four additional infants could not start testing. A previous study has
202 reported that there were no differences of gaze cueing effects on object
203 processing and facial preference in this age range (Ishikawa et al., 2019).
204 The sample size was determined based on a study examining the gaze-
205 cueing effects on infant face perception indexed by ERPs (Jessen &
206 Grossmann, 2020). Using the effect size of gaze cueing from a previous study
207 ($f = .42$), we conducted a priori power analysis using G*Power (Faul,
208 Erdfelder, Buchner, & Lang, 2009). The results indicated that with 14
209 participants in total, we would have achieved above 95% power with an
210 alpha of .05, to find the effects of gaze cueing on infants' face perception
211 indexed by ERPs. The estimated sample size was also sufficient to
212 determine the learning effects of social reward on children's SPNs ($f = .55$,
213 Engle et al., 2021). Because the interaction effect between gaze and learning
214 on SPNs had not been tested before, we conducted a post-hoc power analysis
215 using the effect size from the current study ($\eta p^2 = .751$). The result indicated
216 that with the present sample we have achieved above 95% power with alpha

217 at .05 to find the interaction between gaze and learning.

218 The experimental protocol was approved by the Research Ethics Review
219 Board, Department of Psychology, Doshisha University, Japan. The parents
220 of all participants provided written informed consent before their infants
221 participated in this study.

222

223 **EEG recording**

224 Brain activity was recorded using a wireless EEG system (mBrainTrain,
225 Belgrade, Serbia). The EEG data were recorded from 24 sintered Ag/AgCl
226 electrodes (international 10/20: Fp1, Fp2, F7, Fz, F8, FC1, FC2, C3, Cz, C4,
227 T7, T8, TP9, TP10, CP5, CP1, CPz, CP2, CP6, P3, Pz, P4, O1, and O2;
228 reference: FCz, ground: AFz) with a small wireless amplifier (Smarting
229 mBrainTrain, Belgrade, Serbia) attached to a cap (Easycap, Herrsching,
230 Germany). Recordings were digitized (Smarting Software 3.4.3, Smarting
231 mBrainTrain, Belgrade, Serbia) with a sampling rate of 500 Hz and sent to
232 a computer via Bluetooth. The electrode impedances were maintained below
233 10 k Ω .

234 **Design**

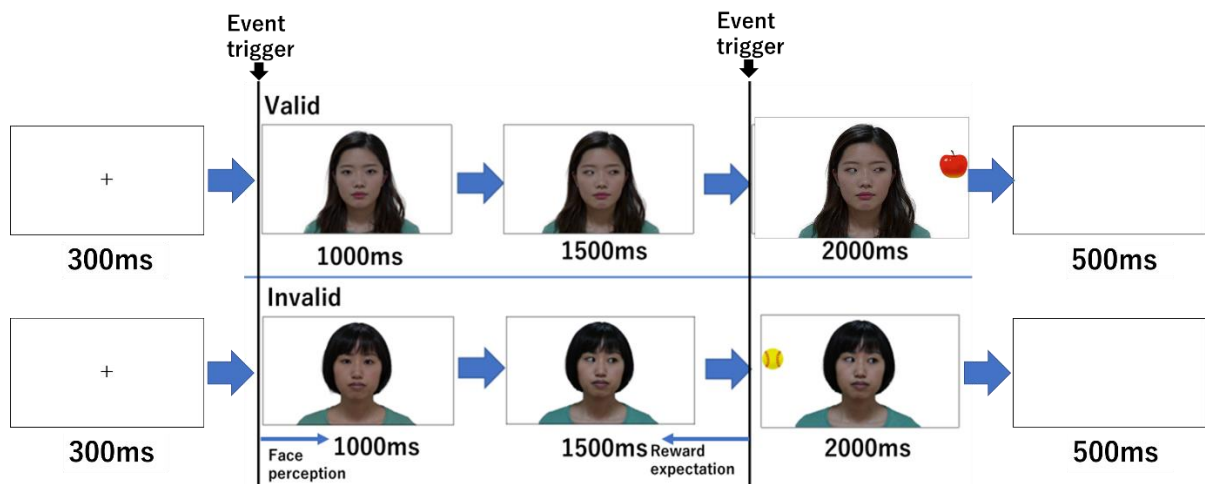
235 The experiment followed a $2 \times 2 \times 2$ design with the within-factors gaze
236 (valid, invalid), learning phase (first half, second half), and hemisphere of
237 electrodes (left, right). To examine learning effects on ERPs with enough
238 trials, we separated all trials to the first half and the second half of the task.
239 For each condition, 32 trials were presented, leading to a total of 128 trials
240 (2 gaze conditions x 2 learning phases). The trial number was determined
241 based on a previous study examining the SPN in three- to four-year-olds
242 (Engle et al., 2021). All trials were presented randomly and consecutively
243 without interruption.

244 **Stimuli and procedure**

245 The experiment was conducted in an electrically shielded chamber. The
246 stimuli were presented on a monitor with a screen size of 1920 \times 1080 and a
247 refresh rate of 60 Hz. Participants were seated in the caregiver's lap,
248 approximately 60 cm from the monitor. The parents were instructed not to
249 interact with the infant during the experiment. During the task, the infant
250 was monitored to record trials in which he or she did not look at the screen.

251 Each trial started with the presentations of a black fixation cross in the
252 center of a white screen for 300 ms followed by a face gazing straight at the

253 observer (see Figure 1). After 1000 ms, the same face was presented with
 254 gaze averted to either the left or right. After 1500 ms, a colorful animation
 255 with sound appeared either on the same side the gaze was directed (valid) or
 256 at the opposite side (invalid). This display was presented for 2000 ms. Each
 257 trial was followed by a blank screen for 500 ms. Because the SPN is
 258 associated with increases in attentional anticipatory systems to rewards in
 259 general (Glazer et al., 2018), we set the duration of gaze cueing according to
 260 the previous study showing a significant gaze cueing effect on attentional
 261 shifts in four- five-month-old infants (Farroni et al., 2000). The animation
 262 was placed approximately 15° to the left or right of the center of the screen.
 263 We used four female faces and six colorful animations for the stimuli.
 264 Pictures of faces were taken for this study. For each experiment, two female
 265 faces were randomly chosen and assigned to the valid and invalid
 266 conditions, respectively. Animations were randomly chosen from six colorful
 267 objects for each trial. We used nonsocial animations for the gaze targets
 268 because we consider that valid gaze cueing to the object can be shared
 269 attention with the social reward, thus the valid condition would be more
 270 rewarding than the invalid condition.



272 Figure 1. Example of trial. A female face was followed by the same face,
 273 gazing either to the side where the animation was going to be presented or
 274 to the opposite side. Models represented in the figure have provided written
 275 permission to publish the images in all formats.

276

277 **ERP data analysis**

278 Data were analyzed using MATLAB (MathWorks, Inc., Natick, MA) and
279 the MATLAB toolbox EEGLAB (Delorme & Makeig, 2004). Artefacts were
280 removed using the following process: First, the data were visually checked
281 for drifts and movement artefacts exceeding 60 μ V and flat-lined data, and
282 trials with those data were excluded. Second, the data were epoched, and
283 eye-blink artefacts were identified through independent component analysis
284 and removed. Data were re-referenced offline to the mean of TP9 and TP10
285 (linked mastoids) and filtered using a bandpass filter of 0.3–30 Hz. The final
286 analysis included participants with at least 15 artefact-free trials in each
287 condition. The mean number of trials contributing to the analysis is
288 following; Valid First half condition: $M = 25.1, SD = 3.56$; Invalid First half
289 condition: $M = 25.25, SD = 3.02$; Valid Second half condition: $M = 24.3, SD =$
290 2.90 ; Invalid Second half condition: $M = 24.85, SD = 3.17$. There were no
291 significant differences in the number of trials among conditions. Also, there
292 were no correlations between age and the number of trials.

293 In adults, the learning effect increases the difference of amplitudes
294 between 600ms and 200ms (SPN) prior to the monetary reward (Morís et al.,
295 2013). Thus, for the analysis of the social reward anticipation, the time-
296 locked epochs of 600 ms preceding the presentation of the animation were
297 extracted and baseline correction was performed to the activity in the –600
298 to –500 ms preceding the presentation of the animation. For the analysis of
299 the face perception, the time-locked epochs of 600 ms following the
300 presentation of a face with direct gaze were extracted and baseline
301 correction was performed to the activity in the –100 to 0 ms preceding the
302 stimulus.

303 We analyzed the mean amplitudes at occipital electrodes (O1, O2) in a
304 time window between 270 and 320 ms (N290) and 380 and 430 ms (P400)
305 after the presentation of a face gazing straight. In addition, we analyzed the
306 mean amplitudes at the frontal electrodes (F3, F4) in a time window
307 between 200 ms and 0 ms (SPN) before the presentation of animation. The
308 electrodes were chosen based on prior studies (Parise, Handl, & Striano,
309 2010; Peykarjou, Pauen, & Hoehl, 2014; Walentowska et al., 2018). The time
310 windows were based on a visual inspection of the present data.

311 We performed a repeated-measures ANOVA with gaze (valid, invalid),
312 learning phase (first half, second half), and hemisphere (left, right) as

313 within-subjects factors. We reported effect sizes as partial eta square (ηp^2)
314 for ANOVAs.

315

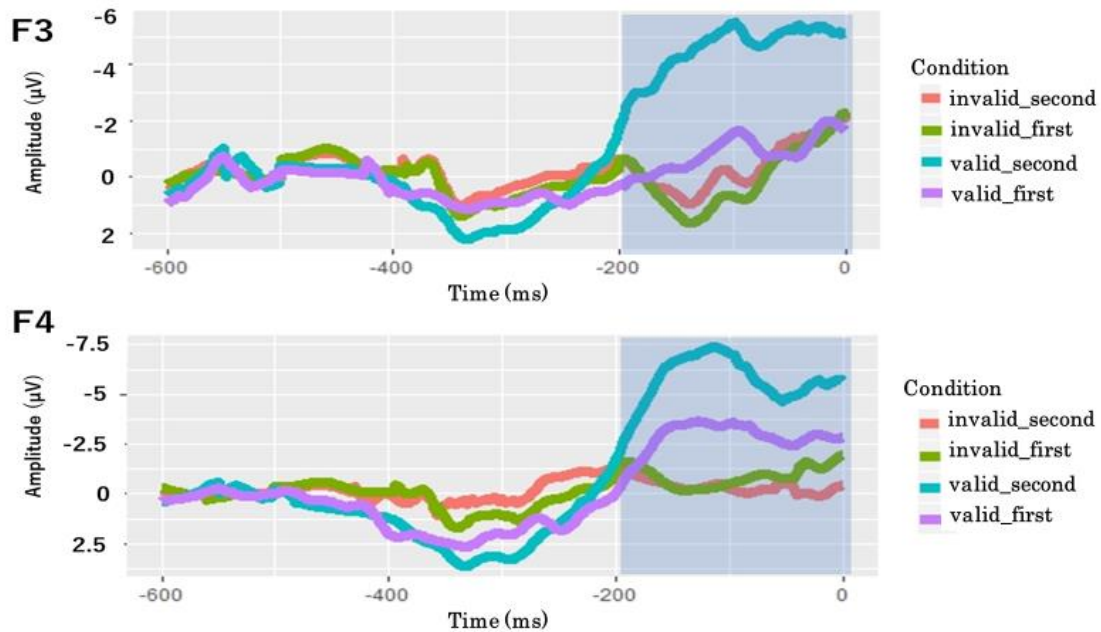
316 **Results**

317 SPN

318 Figure 2 shows ERP responses before the presentation of animation. At
319 the frontal electrodes (F3, F4), we observed a significant interaction effect
320 between the gaze and learning phase in SPN amplitudes ($F(1,19) = 57.224$, p
321 $< .001$, $\eta p^2 = .751$). Post-hoc t -tests corrected by the Holm method revealed
322 that a greater amplitude of SPN was found in the second half of the learning
323 phase than in the second half in the valid condition ($p < .001$). In the invalid
324 condition, there was no significant difference in the SPN amplitudes
325 between learning phases ($p = .233$). In the second half of the learning phase,
326 the SPN amplitude in the valid condition was greater than that in the
327 invalid condition ($p < .001$). There were no other significant interactions
328 (gaze \times learning \times hemisphere: $p = .084$, $\eta p^2 = .149$; learning \times hemisphere:
329 $p = .132$, $\eta p^2 = .116$; gaze \times hemisphere: $p = .089$, $\eta p^2 = .145$).

330 The main effect of learning was significant with greater amplitudes in the
331 second half of the learning phase than in the first half of the learning phase
332 ($F(1,19) = 57.058$, $p < .001$, $\eta p^2 = .758$). Also, the main effect of gaze was
333 significant with greater amplitudes in the valid condition than in the invalid
334 condition ($F(1,19) = 59.636$, $p < .001$, $\eta p^2 = .750$). There were no significant
335 main effect of hemisphere ($F(1,19) = .230$, $p = .637$, $\eta p^2 = .012$).

336



337

338 Figure 2. ERP responses from baseline (-600 to -500ms) at frontal electrodes
 339 (F3, F4). No differential response was observed between learning phases in
 340 the invalid condition. In contrast, a larger SPN response was elicited in the
 341 second half of the learning phase in the valid condition compared to the first
 342 half.

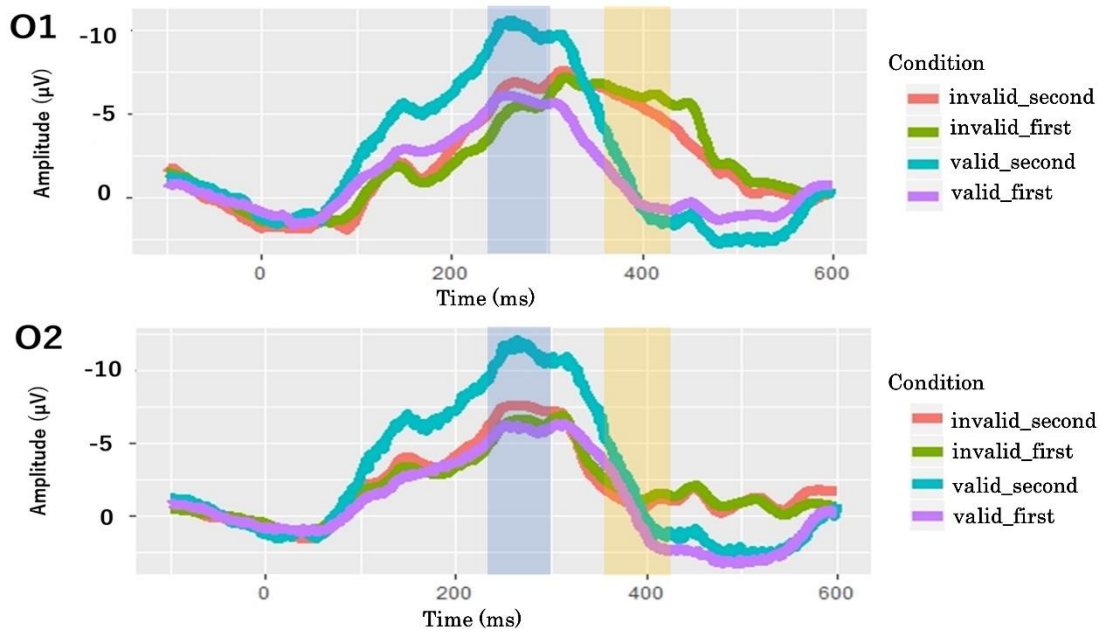
343

344 N290

345 Figure 3 shows ERP responses after the presentation of a face. At occipital
 346 electrodes (O1, O2), we observed a significant interaction effect between the
 347 gaze cueing and learning phases in N290 amplitudes ($F(1,19) = 29.359$, p
 348 $< .001$, $\eta p^2 = .607$). Post-hoc t-tests corrected by the Holm method revealed
 349 that a greater amplitude of N290 was found in the second half of the
 350 learning phase than in the first half in the valid condition ($p < .001$). In the
 351 invalid condition, there was no significant difference in N290 amplitudes
 352 between learning phases ($p = .699$). In the second half of the learning
 353 phases, the N290 amplitude in the valid condition was greater than that in
 354 the invalid condition ($p = .008$). There were no other significant interactions
 355 (gaze \times learning \times hemisphere: $p = .809$, $\eta p^2 = .003$; learning \times hemisphere:
 356 $p = .119$, $\eta p^2 = .123$; gaze \times hemisphere: $p = .408$, $\eta p^2 = .036$).

357 The main effect of learning was significant with greater amplitudes in the
 358 second half of the learning phase than in the first half of the learning phase
 359 ($F(1,19) = 61.105$, $p < .001$, $\eta p^2 = .763$). There were no significant main

360 effects (gaze: $F(1,19) = 2.386$, $p = .139$, $\eta p^2 = .112$; hemisphere: $F(1,19) =$
 361 3.405 , $p = .081$, $\eta p^2 = .152$).



362

363 Figure 3. ERP responses from baseline (-100 to 0ms) at occipital electrodes
 364 (O1, O2). A larger N290 response was elicited in the second half of the
 365 learning phase in the valid condition compared to the first half. The valid
 366 conditions showed a larger P400 response than the invalid conditions.

367

368 P400

369 At occipital electrodes (O1, O2), we observed a significant interaction
 370 effect between gaze cueing and hemisphere in P400 amplitudes ($F(1,19) =$
 371 8.82 , $p = .008$, $\eta p^2 = .317$). Post-hoc t-tests corrected by the Holm method
 372 revealed that a greater amplitude of P400 was found at O2 than at O1 in
 373 the invalid condition ($p < .001$). At each electrode, greater amplitudes were
 374 found in the valid condition than in the invalid condition (O1: $p < .001$; O2: p
 375 $< .001$).

376 There were no other significant interactions (gaze \times learning \times hemisphere:
 377 $p = .291$, $\eta p^2 = .059$; gaze \times learning: $p = .114$, $\eta p^2 = .126$; learning \times
 378 hemisphere: $p = .177$, $\eta p^2 = .094$). The main effect of gaze was significant
 379 with greater amplitudes in the valid condition than in the invalid condition
 380 ($F(1,19) = 69.877$, $p < .001$, $\eta p^2 = .786$). The main effect of hemisphere was
 381 also significant with greater amplitudes in the O2 than in the O1 ($F(1,19) =$

382 13.075, $p = .002$, $\eta p^2 = .408$). There were no significant main effects of
383 learning ($F(1,19) = .679$, $p = .420$, $\eta p^2 = .034$).

384

385 **Discussion**

386 This study aimed to investigate neural responses during social reward
387 anticipation in early infancy. In particular, we examined the other's gaze
388 cueing effects on the social reward anticipations indexed by the SPN. As we
389 predicted, we found that repeated experience of another's valid gaze cueing
390 elicited a larger SPN before the presentation of the animation, suggesting
391 that infants started to anticipate the social reward after learning
392 associations between the face, the validity of gaze cueing, and the events of
393 shared attention. In line with a previous study showing that social cues
394 elicited the SPN at preschool age (Engle et al., 2021), the gaze cues
395 predictive to the social reward of shared attention elicited a larger SPN than
396 invalid gaze cues. This finding suggests that infants around seven months
397 old could learn associations between faces and events of shared attention,
398 and these experiences evoke the social reward anticipations. In the current
399 study, the same animations were presented under both valid and invalid
400 conditions. Thus, the difference in events was whether the face gazed
401 toward the animation. Looking to the same object with another has been
402 suggested as a rewarding event, and infants are motivated to engage in the
403 situation of shared attention (Clifford & Dissanayake, 2008; Mundy, Card, &
404 Fox, 2000). It is considered that the SPN was observed because infants
405 anticipated that situations of shared attention would occur. Recent studies
406 suggest that infants expect social reward before following others' gaze
407 direction toward an object (Ishikawa, Senju, & Itakura, 2020; Ishikawa et
408 al., 2022). After learning the validity of gaze cueing, infants recognize which
409 face induces valid cueing and can anticipate the social reward of shared
410 attention.

411 Furthermore, we investigated how the learning of others' gaze validity
412 affects face perception by measuring N290 and P400 responses. We found
413 that the N290 amplitudes were increased in the second half of the learning
414 phase that others' gaze cues were valid, suggesting that knowledge of others'
415 gaze validity affects face perception. Observing others' gaze behaviours can
416 modulate face perception from early infancy. A behavioural study indicates
417 that the face providing valid gaze cueing toward the target object is

418 preferred over the face, providing invalid gaze cueing (Ishikawa et al.,
419 2019). Adult studies have shown that gaze cueing affects facial evaluations.
420 For example, it has been reported that the faces that consistently looked
421 towards targets were evaluated as more trustworthy than the faces that
422 consistently looked away from targets (Bayliss, Griffiths, & Tipper, 2009;
423 Bayliss & Tipper, 2006). Observing others' valid gaze cueing situations may
424 be memorized as positive events, and this knowledge of faces affects face
425 perception and evaluations.

426 The experience-based modulation of N290 has been reported in cultural
427 studies. For example, Balas et al. (2011) tested infants' N290 with faces of
428 either their own race or a different race. They showed that nine-month-old
429 infants who had experience primarily with Caucasian faces elicited a larger
430 N290 in response to Caucasian faces, compared to African faces. It was
431 suggested that this cultural modulation on N290 would be related to social
432 experience in each developmental environment. Not only the long-term
433 experience in development, but the visual experience in the experimental
434 setting also modulates the N290. It has been suggested that the N290 is
435 sensitive to the repetition of female faces, linked to the greater visual
436 experience with female faces (Righi et al., 2014). Thus, N290 may be
437 sensitive to learning effects with repetitive experiences of the social reward
438 of shared attention.

439 Inconsistent with our hypothesis, we did not find an interaction between
440 gaze cueing and learning effects in the P400 responses. However, the faces
441 in the valid conditions elicited larger P400 responses than those in the
442 invalid conditions without the learning effect. It is considered that even a
443 small amount of experience can influence face perception, as reflected in the
444 P400. A behavioural study in infants reported that only 12 trials of gaze-
445 cueing situations enhanced face preference for the valid gaze leader
446 (Ishikawa et al., 2019). Although the presentation time of the gaze cueing
447 situation in their study is different from this study, face recognition indexed
448 by P400 responses may be more sensitive to memory modulation than N290.
449 It has been shown that infant P400 responds differentially to familiar
450 versus unfamiliar faces (Scott, Shannon, & Nelson, 2006), suggesting that
451 the P400 is sensitive to the memory of faces. Thus, in this study, it is
452 possible that infants rapidly learned which face provided valid cues, and
453 this memory of faces modulated the P400. Moreover, the greater P400 can

454 reflect enhanced attention to faces (Xie et al., 2019). Infants may have paid
455 more attention to the valid face after they learned the conditions of faces.
456 Another possibility is that the P400 only reflects facial categories (i.e., valid
457 or invalid) and may not be modulated by higher-order social reward
458 anticipations learned through repetitive experiences. Peykarjou et al. (2016)
459 reported that N290 was modulated by the repetitive presentation of faces,
460 while there was no repetition effect on P400. In line with this previous
461 study, we did not observe any learning effects on P400. It has been
462 suggested that both N290 and P400 show similar functional characteristics
463 to the adult N170 ERP component (De Haan et al., 2003; Hoehl &
464 Peykarjou, 2012; Luyster et al., 2011). However, the functional differences
465 between these two components in infants remain unclear. Why memory
466 modulation of face perceptions differs between N290 and P400 should be
467 addressed.

468 This study used the situation of shared attention as the social reward;
469 however, we did not measure infants' looking behaviour using eye-tracking
470 techniques. Without eye tracking, it is unclear how infants engaged in gaze
471 following and shared attention. Most infant ERP studies examining gaze
472 cueing effects have not used eye-tracking (Reid et al., 2004; Hoehl et al.,
473 2008; Hoehl & Striano, 2010; Hoehl et al., 2014; Jessen & Grossmann,
474 2020), and they have discussed effects of shared attention on infant
475 cognitive processing based on the ERP results. However, future studies
476 should use simultaneous measurements of eye-tracking and EEG
477 recordings. Another limitation of this study is that it is unclear how many
478 experiences are necessary to elicit infants to anticipate social rewards.
479 Usually, ERP studies require comparatively more trials than behavioural
480 studies. It is possible that infants could learn associations between face,
481 gaze validity, and social reward timing with fewer experiences than the trial
482 numbers in the current study. Recently, the single-trial EEG technique has
483 been used to examine trial-by-trial neural responses to predict adult
484 behavioural performance (Si et al., 2020). Using single-trial EEG, it will be
485 possible to test how infants start to anticipate future events during
486 repetitive experiences. In addition, high-density EEG recordings may help
487 to understand the cognitive processing during association learning. A recent
488 study examining the reliability of topographic analysis at different electrode
489 densities has suggested that the use of a small number of channels less than

490 32ch is not recommended (Zhang et al., 2021). Due to the small number of
491 electrodes (24ch), our data cannot provide reliable topographic data. EEG
492 topographic data with high electrode densities will provide insights into
493 temporal and spatial information of infant brain activations. The current
494 study did not include non-social cues such as arrows. It is possible that
495 infants anticipate the perceptually rewarding animation position from the
496 predictive cue rather than anticipating the social reward of shared
497 attention. It is necessary to measure the SPN to valid cueing arrows and
498 compare the SPN between social and non-social cues.

499 A future direction from a broader perspective is investigating what can
500 motivate or drive infants' social behaviour in real interactions. The second-
501 person neuroscientific approach has been growing to elucidate the
502 behavioural and neural mechanisms of social interactions (Redcay &
503 Schilbach, 2019). In this framework, neural processes are examined within
504 the context of a real-time reciprocal social interaction. Studies using second-
505 person approaches have shown that a complex brain network associated
506 with mentalizing, attention, and reward processing is involved in joint
507 attention (Mundy, 2018). Gaze communications such as eye contact can
508 affect motivations (Ishikawa & Itakura, 2022). Also, in real interactions,
509 different factors such as another's affective states and saliency of the target
510 object may modulate gaze following and joint attention. To understand the
511 neural mechanisms of infants' motivation for social behaviour, the second-
512 person framework is essential.

513 In summary, we indicated that infants around seven-months-old show a
514 larger SPN after learning the validity of others' gaze cueing. Infants could
515 anticipate the social reward of shared attention by perceiving others' gaze
516 cueing. In addition, knowledge of the validity of others' gaze modulated face
517 perception, indexed by the N290. The experience of shared attention could
518 affect not only the anticipation of the social reward but face perceptions.

519

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525

526 **Conflict of interest**

527 The authors have no conflicts of interest.

528

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534

535 **Author contributions**

536 M.I. and S.I. developed the study concept. M.I. conducted the experiments
537 and analysed the data. M.I. and S.I. the authors approved the experimental
538 design and discussed the results. S.I. supervised the study.

539

540 **Data accessibility**

541 Data used in the analysis are available in figshare
542 (<https://doi.org/10.6084/m9.figshare.18636803.v1>).

543

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