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1 **The Developmental Origins of Gaze-Following in Human Infants**

2 Teresa Del Bianco*^{1,2}

3 Terje Falck-Ytter^{3,4}

4 Emilia Thorup³

5 Gustaf Gredebäck³

6 ¹ Department of Psychology and Cognitive Science, University of Trento

7 ² Centre for Brain and Cognitive Development, Department of Psychological
8 Sciences, Birkbeck University of London

9 ³ Uppsala Child and Babylab, Department of Psychology, Uppsala University

10 ⁴ Center of Neurodevelopmental Disorders (KIND), Karolinska Institutet

11

12 * Corresponding author.

13 Address: Henry Wellcome Building, Centre for Brain and Cognitive Development, 32
14 Torrington Square, London WC1E 7JL

15 Phone: +44 020 7631 0764

16 Email: t.delbianco@bbk.ac.uk

17

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22

Abstract

23

During the first year of life, infants develop the capacity to follow the gaze of others.

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This behaviour allows sharing attention and facilitates language acquisition and cognitive

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development. This article reviews studies that investigated gaze-following before 12 months

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of age in typically developing infants and discusses current theoretical perspectives on early

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GF. Recent research has revealed that early GF is highly dependent on situational constraints

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and individual characteristics, but theories that describe the underlying mechanisms have

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partly failed to consider this complexity. We propose a novel framework termed the

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perceptual narrowing account of GF that may have the potential to integrate existing

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theoretical accounts.

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Key words:

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Gaze-following, infant development, shared attention

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37 A baby is having a good time with her mother: the mother looks at her baby and then
38 shifts gaze towards a nearby toy and says "ball." The infant turns her eyes in the same
39 direction, following her mother's gaze. This phenomenon brings the same object to the foveal
40 vision of both interaction partners, which is known as gaze-following (GF; Moore, 2008).

41 Scaife and Bruner (1975) were the first to investigate the emergence of GF from age 2
42 months and found out that younger infants rarely exhibit GF but that it progressively becomes
43 a frequent response over the first year of life. Their study has been criticized on
44 methodological grounds (Corkum & Moore, 1998), but the study was nonetheless important
45 because it laid the foundation for subsequent works. Scaife and Bruner (1975) argued that GF
46 develops from either a specific sensitivity to social signals or a basic response to perceptual
47 cues, such as the warning signals that many animals use in the face of a threat. The authors of
48 subsequent studies (Butterworth & Cochran, 1980; Butterworth & Jarrett, 1991) proposed
49 that GF develops from an innate predisposition and that maturational constraints explain the
50 pattern of change over the first year, whereas environmental factors play little role. With a
51 series of studies, Moore and collaborators (Corkum & Moore, 1995, 1998; Moore,
52 Angelopoulos, & Bennett, 1997; Moore & Corkum, 1998) challenged both views arguing for
53 a reinforcement learning account of GF (Corkum & Moore, 1998). Most of the research to
54 date has fueled this debate, and although several theories have been proposed, the field has
55 yet to reach a common understanding about the foundational mechanism(s) behind the
56 emergence of GF during the first year of life.

57 **Aim of This Review**

58 Despite the importance of GF, no dedicated review has surveyed the current state-of-
59 art. Two important books need to be acknowledged: "Autism and Joint Attention:
60 Development, Neuroscience, and Clinical Foundations" (Mundy, 2016), which addresses the

61 development of joint attention behaviors (including GF) in typical and atypical development,
62 and “Gaze Following: Its Development and Significance” (Flom, Lee, & Muir, 2007), which
63 reviews studies on GF emergence published up to the year 2007. After more than 10 years, an
64 updated review is needed given the methodological advancements in the field (e.g., change
65 from manual coding of gaze-shifts to eye-tracking, and uprise of longitudinal studies), and
66 the newly revitalized debate over theories that were published during in the last decade (e.g.,
67 the Natural Pedagogy, Csibra & Gergely, 2008, and the new insights into the deficits of social
68 orienting in Autism Spectrum Disorder, Mundy, 2016). Therefore, we bring into focus the
69 emergence of GF in the first year of life, by integrating early and recent research, and
70 theoretical insights published after 2007, after a brief methodological note about how GF is
71 measured. The first part of the review deals with GF protracted development; it will be clear
72 that GF is neither innate and automatic, nor belated or subtle. In sum, GF emerges early and
73 is influenced by the properties of the target objects, the interaction partners, the infants’ eye-
74 gaze responsiveness and characteristics. Yet, as we summarise in the Theoretical Perspectives
75 section, there is no agreement on the interpretation of the current evidence, which prevents
76 sharp conclusions on the developmental origins of GF. We conclude our review with a
77 theoretical proposal that integrates existing theories into a novel framework.

78 **Defining and Measuring GF in Infants**

79 GF is often measured in a context in which a model moves her head and eyes from a
80 central location towards one of two targets placed symmetrically on either side of her.
81 Alternatively, the model turns torso, head, and eyes (e.g., the *Early Social Communication*
82 *Scale*; Morales, Mundy, Delgado, Yale, Neal, et al., 2000) – or the eyes only (Moore &
83 Corkum, 1998). An experimenter (Moore & Corkum, 1998) or the infant’s mother (Morales,
84 Mundy, & Rojas, 1998) usually plays the role of the model. Each trial often includes an

85 initial period of interaction to attract the infant's attention to the adult's face: it lasts a few
86 seconds (Gredebäck, Theuring, Hauf, & Kenward, 2008) or continues until the infant is
87 engaged (D'Entremont, Hains, & Muir, 1997). The targets are usually a pair of toys on a table
88 (Gredebäck, Fikke, & Melinder, 2010) or posters (Mundy et al., 2007) and monitors (Deák,
89 2015).

90 GF is present when the infant shifts her gaze from the model's face to the object that
91 the model looks at more often than would be expected by chance. The tendency to follow a
92 gaze is often measured as a difference score, the number of trials with a correct gaze shift
93 minus the number of trials with an incorrect gaze shift, and GF is defined as a difference
94 score significantly above zero (Corkum & Moore, 1995). Other studies rely on the percentage
95 of trials in which GF is observed, and include trials with no shifts in the total number of trials
96 (Gredebäck et al., 2010). The infant's gaze shifts can be coded from videos (D'Entremont,
97 2000), by recording the infant's field of view with a head-mounted camera (Yoshida &
98 Smith, 2008) or with eye tracking (Theuring, Gredebäck, & Hauf, 2007). Some studies also
99 assess the degree to which infants look more towards the attended, than the unattended object
100 (for instance, see Senju, Vermetti, Ganea et al., 2015; Theuring, Gredebäck, & Hauf, 2007;
101 Thorup, Kleberg, & Falck-Ytter, 2017). Regarding the specific definition of the behavior
102 being used to produce the GF cue, it depends on the body part that the model used to turn:
103 some authors oppose the use of GF when head and eyes are shifted together because the
104 response to this action might involve motion-cueing (Deak, 2015). Nonetheless, the majority
105 of studies addressing GF development during the first year involve a model shifting head and
106 eyes congruently. Therefore, while using the term GF for simplicity and assuming that the
107 model moved head and eyes together, throughout the review, we will specify only when
108 relevant whether the study involved head and eyes together or the eyes alone. Beyond this
109 controversy, in these contexts, the infant's overt gaze shift is considered to be motivated by

110 the direction of the adult's gaze (Zuberbühler, 2008) and not reflexively triggered by the
111 appearance of targets as in attentive cueing paradigms (Frischen, Bayliss, & Tipper, 2007).

112 **Development of GF in the First Year**

113 **Before GF: the development of gaze cueing**

114 It has been suggested that newborns, as well as older infants (Hood, Willen, & Driver,
115 1998), show a *rudimentary* form of GF because they orient to targets that appear in the
116 direction cued by eye-gaze (Farroni, Massaccesi, Pividori, & Johnson, 2004). In that study,
117 newborns were presented with an image of a schematic face moving her eyes to the side and
118 a target popping out congruently or incongruently with the direction of the eye-gaze. Because
119 the figure cued a location with the eye-gaze rather than shifting the eyes towards a visible
120 object, this paradigm is better described as gaze cueing (Frischen et al., 2007) or gaze-
121 priming (Gredebäck & Daum, 2015), rather than as GF. The process underpinning gaze
122 cueing involves a covert shift of attention (i.e., without a concurrent eye-movement; Frischen
123 et al., 2007) in the direction cued by the eye-gaze (Gredebäck & Daum, 2015) or motion
124 (Farroni, Johnson, Brockbank, & Simion, 2000). Below 6 months of age, gaze cueing
125 enhances the level of processing of gazed-at targets, estimated as the looking time on targets
126 (Theuring et al., 2007) and the amplitude of brain electrophysiological responses (event-
127 related potentials) associated with memory and information-processing (Hoehl, Wiese, &
128 Striano, 2008; Wahl, Michel, Pauen, & Hoehl, 2013). These findings and the fact that gaze
129 cueing has the same outcome as GF (i.e., bringing the same object into attention of two
130 interaction partners) tentatively suggest that gaze cueing might play a role in the development
131 of GF. Unfortunately, longitudinal studies that assess the development of both gaze cueing
132 and GF are lacking, even though such studies could unravel the early ontogeny of GF from
133 birth.

134 Development of spontaneous GF

135 Spontaneous GF, where infants follow a model shifting her eyes and head to a visible
136 target, starts to emerge between 3 and 6 months of age. Some studies have claimed to
137 demonstrate GF tendencies already at 3-4 months of life (Butterworth & Jarrett, 1991;
138 D'Entremont, 2000; Gredebäck et al., 2010; Hoehl, Wahl, Michel, & Striano, 2012; Perra &
139 Gattis, 2010; though see Deák, 2015, for criticism of this work). Early GF is not always
140 precise – infants often look at the closest object in the model's gaze direction (Butterworth &
141 Jarrett, 1991) – or specific, because the direction of the head movement prevails in directing
142 infants' attention (Tomasello, Hare, Lehmann, & Call, 2007). GF becomes more pronounced
143 around age 6 months, both when stimuli are presented on a screen (Gredebäck et al., 2008)
144 and in structured social interactions (D'Entremont, 2000). The latency of gaze shifts (the time
145 from the onset of the model's gaze shift to the onset of the infant's shift to the same direction)
146 is initially rather long and decreases over time: from about 3 seconds at 3 months to slightly
147 more than 1 second at 8 months of age (D'Entremont, 2000; Gredebäck, Fikke, & Melinder,
148 2010). However, in live, uncontrolled settings, the latency of GF can be even longer (16
149 seconds at age 3 months and 8 seconds at 9 months, as reported by Striano & Stahl, 2005).
150 These findings suggest that infants not only become more accurate at following gaze but that
151 the process increases speed with age (though it should be noted that the oculomotor system at
152 large demonstrates similar decreases in reaction time in other, non-social, settings;
153 Gredebäck, Örnkloo, & Von Hofsten, 2006; Kenward et al., 2017).

154 GF during the first year of life is not simply a response to any-and-all shifts of
155 attention by a caregiver: the behavior depends on the properties of the elements that are
156 readily available in an infant's close environment, the target object, and the interaction
157 partners. Furthermore, infant-related factors that act as precursors and influence later

158 correlates of GF are important to place GF into the typical (and atypical) developmental
159 context. Support for each of these contextual and individual differences is addressed below.

160 **Properties of the target objects**

161 Infants younger than 12 months rarely follow gaze to objects outside of their field of
162 view (e.g., behind of them; Butterworth & Jarrett, 1991; Corkum & Moore, 1995; Deák,
163 Flom, & Pick, 2000). The proximity necessary for GF starts to expand after 6 months of age
164 (Butterworth & Jarrett, 1991). In addition, GF appears to be most efficiently elicited in the
165 context of salient but not overly interesting objects. For instance, toys that attract too much
166 attention, such as moving stuffed animals (D'Entremont, 2000), reduce the tendency to
167 follow a gaze, compared to static targets. When the properties of targets are manipulated
168 contingently to when the child is following the direction of gaze to that object, it is possible
169 to increase the frequency of GF over time (Deák, 2015; Moore & Corkum, 1998).

170 Taken together, these results suggest that there might be a U-shaped association
171 between GF frequency and the saliency of targets and distractors. That is, objects that are
172 interesting or have previously *reacted* when the infant attended to them, but that do not
173 distract the infant or reduce the infant's attention on the model's face and her relocation of
174 attention, elicit the maximum GF frequency.

175 **Factors related to social partners**

176 The social partner can perform actions that increase the infant's tendency to follow
177 the direction of gaze, including eye contact, infant-directed speech (Senju & Csibra, 2008),
178 and attention-grabbing movements without social connotations, such as head-shaking
179 (Szufnarowska, Rohlfsing, Fawcett, & Gredebäck, 2014). The identity of the person
180 performing the gaze cue can also influence GF. In a longitudinal study, Gredebäck and
181 colleagues (2010) reported that GF is expressed earlier during live interactions with a
182 stranger than during interactions with the infant's mother. In this study, the infant's eye-

183 movements were recorded with an eye-tracker while the infant interacted with either a female
184 stranger (an experimenter) or her own mother (50% of the infants). The experimenter/the
185 mother placed two toys next to them and were instructed to engage the infant and shift their
186 head and eyes toward one of the two toys. Two measures of GF – the differential score and
187 the percentage of correct gaze shifts on the total number of trials – revealed a consistent
188 growth pattern between 4 and 6 months in the stranger condition, while GF remained at
189 chance level in the mother condition up until 6 to 8 months. A previous longitudinal study
190 (Striano & Bertin, 2005) showed similar results, even though the authors used a less
191 structured paradigm (i.e., free-play with a stranger/the infant's mother), coded the videos
192 manually and operationalized GF with a slightly more restricting criteria (i.e., the infants had
193 to look at the toy before engaging with the adult). Despite the methodological differences,
194 this study found that infants from 5 to 9 months of age increased their tendency to follow
195 gaze only during stranger–infant interactions. At the same time, event-related potentials
196 studies demonstrate that in 4-month-olds who interact with their parents, relative to strangers,
197 stronger positive slow wave responses are associated with enhanced attention to the target
198 being attended to during GF (Hoehl et al., 2012). Even though based on a small set of studies,
199 we may hypothesize that novelty (associated with strangers) might strengthen the focus of
200 attention on others and their gaze and that familiarity (e.g., the mother) might strengthen the
201 focus of attention on the objects targeted by the gaze.

202 Finally, a longitudinal study by Senju et al. (2015) demonstrated that GF emerges
203 even in children whose parents are blind. This finding suggests that GF could develop even if
204 the caregiver's gaze does not regularly predict interesting sights, and challenges views that
205 capitalize on social motivation and reward (see dedicated sections).

206 Factors Related to the Infant: Precursors and Later Correlates**207 Responsiveness to eye-gaze**

208 It has been claimed that infants respond to isolated eye movements significantly later
209 than they start to respond to head movement (18 months according to Moore & Corkum,
210 1998). However, one eye-tracking study demonstrated spontaneous eye-gaze following many
211 months before (at age 10 months; Thorup, Nyström, Gredebäck, Bölte, & Falck-Ytter, 2016).
212 Still, young infants shift their gaze in the direction of head movement, even when it is in the
213 opposite direction of the movement of the eyes (Tomasello et al., 2007) or when the eyes of
214 their interaction partner are closed and the target is occluded from their interaction partners'
215 sight (Brooks & Meltzoff, 2002, 2005; Caron, Butler, & Brooks, 2002). The situation reverts
216 by the end of the first year: at age 10 months, an infant differentiates between open and
217 closed eyes and will follow the direction of head movement only when the model shifts her
218 head with open eyes (Brooks & Meltzoff, 2005). Finally, at around age 12 months, infants
219 follow the direction of another's eyes, even when the head moves in the opposite direction
220 (Tomasello, Hare, Lehmann, & Call, 2007). We propose that infants follow gaze with a social
221 motivation but that the head provides a disproportionate saliency— as gaze direction is a
222 combination of the direction of the head and eyes. One way to view this transition from
223 tracking many objects and faces to tracking eyes reflects a narrowing of conditions that elicit
224 GF. We tentatively suggest that this change might be a perceptual narrowing process similar
225 to that demonstrated for face perception (Scott, Pascalis, & Nelson, 2007). Early in life gaze
226 shifts follow a broad range of signals, over time the conditions that lead to GF narrow down
227 to a small set of social signals indicating that others attend to a particular location in the
228 world. The notion of perceptual narrowing in GF is further elaborated upon towards the end
229 of the review.

230 Individual differences

231 To date, investigations of the influence of individual characteristics on GF have not
232 been systematic, and few and largely unrepeated studies are available. Such studies report
233 that enhanced GF is associated with a visual preference for humans (as opposed to geometric
234 patterns; Imafuku et al., 2017), parental reports of high sociability (Striano & Rochat, 1999),
235 and sustained focus of attention in everyday situations at 6 months of age (Morales et al.,
236 2000); however, an abbreviated focus of attention is associated with more frequent GF in
237 novel situations at 11 (Todd & Dixon, 2010). In addition, low levels of negative affect (e.g.,
238 fear and frustration; Salley & Dixon, 2007) and surgency (e.g., perceptual sensitivity; Todd &
239 Dixon, 2010) are positively associated with enhanced GF. Studies on individual differences
240 between infants and their capacity for GF are important as they have the potential to inform
241 theory about the conditions that foster and hinder the development of GF. Unfortunately, the
242 number of longitudinal studies are few and current finds are at best tentative. Further studies
243 with a more in-depth focus on individual differences in the context of the development of GF
244 are clearly needed.

245 Language

246 Longitudinal studies have demonstrated that GF is associated with language
247 acquisition and can predict word comprehension and vocabulary (Morales et al., 2000;
248 Mundy et al., 2007; Tenenbaum et al., 2015). In the period between 6 and 12 months of age,
249 when infants happen to gaze at a face, the frequency of GF is correlated with the amount of
250 attention dedicated to the mouth, an index of ongoing language acquisition (Tenenbaum et
251 al., 2015). GF and language acquisition appear to go hand in hand; indeed, the infant's GF
252 between 6 and 18 months of age could predict receptive and expressive language outcomes at
253 1-2 years of age (Morales et al., 2000; Mundy et al., 2007; Tenenbaum et al., 2015). In
254 particular, infants who are better at GF develop a larger vocabulary between age 14 and 30

255 months than infants with less GF ability (Brooks & Meltzoff, 2005; Markus, Mundy,
256 Morales, Delgado, & Yale, 2000; Mundy et al., 2007; Tenenbaum et al., 2015). One study
257 showed that the combination of GF and an infant's vocalizations interacted to predict word
258 comprehension at 14–18 months of age (Brooks & Meltzoff, 2005). Those authors
259 hypothesized that at an age when infants start to grasp the referential meaning of gaze,
260 vocalizations may represent a “preverbal effort” to communicate actively with the social
261 partner behaviour that may play a role in the progression of linguistic skills (Brooks &
262 Meltzoff, 2005). However, to validate this idea, studies are needed that target the meaning of
263 this preverbal effort.

264 **Sustained attention**

265 The development of spontaneous GF before 6 months of age and long response
266 latencies of GF in the first year of life that we mentioned before (D'Entremont, 2000) might
267 be explained by the initially immature cortical frontal areas and executive functions (Canfield
268 & Kirkham, 2001): one interesting aspect of executive function is that sharing attention
269 through GF may contribute to maturation. Apart from increasing the time spent fixating on a
270 specific object that is being looked at (Brooks & Meltzoff, 2005; Senju et al., 2015), bouts of
271 joint attention between an infant and a parent, including GF, might prolong the infant's
272 average fixation duration in general, a form of executive function also termed “sustained
273 attention” (Yu & Smith, 2016). According to Yu and Smith (2016), sustained attention may
274 specifically increase as a function of the parent's responsiveness. This hypothesis is
275 supported by data showing that at the end of the first year, GF is correlated with the duration
276 of visual orienting (Morales et al., 2000) and longitudinally predicts self-regulatory behavior
277 (Vaughan Van Hecke et al., 2012) – suggesting that both phenomena may be partly mediated
278 by the same process, i.e., executive function (Vaughan Van Hecke et al., 2012). However, to

279 date, no study has investigated the direct relationship between GF, as it first emerges, and the
280 self-regulation of attention and executive function.

281 In sum, GF during infancy depends on the ability to follow others' gaze and on
282 external factors such as the context in which GF occurs, the person with whom infants
283 interact, and the dispositional attributes of the infant. Moreover, GF influences infants' social
284 outcomes, e.g., language development, and likely affects more general abilities, such as
285 attention regulation. Contrary to first accounts, these findings suggest that GF is a dynamic,
286 transferable skill that positively influences infant functional adaptation to a cluttered social
287 environment.

288 Furthermore, the growing interest in the early diagnosis of Autism Spectrum Disorder
289 (ASD) has motivated the investigation of whether differences in the earliest behavioural
290 expressions of social orienting, such as GF, might predict atypical development. Research in
291 the field of social orienting in ASD is immense, and certainly beyond the scope of this
292 review. However, the approach to the social orienting deficit in ASD have progressed from
293 postulating the lack of specific abilities (e.g., accurate GF), to general regulating functions
294 (e.g., GF occurring spontaneously during social interactions; for a review, see Senju, 2013
295 and Mundy, 2016). This view is clearly in line with the idea that GF *is not simply a response*
296 *to any-and-all shifts*; in the case of ASD, atypical development is an additional feature that
297 influences GF – thus, GF is a good candidate to track atypical development. Below, we
298 briefly introduce the field of study where ASD and GF intersect and focus on longitudinal
299 studies that have yielded evidence regarding the predictive power of GF in ASD diagnosis.

300

ASD

301 ASD affects 1–1.5% of the population (Baird et al., 2006) and is characterized by
302 impairments in social communication and interaction, restricted and repetitive behaviors and

303 interests (American Psychiatric Association, 2013). The relation between GF and ASD is
304 complex, and a full account of the area is out of the scope of this review (for an extensive
305 review see Mundy, 2016). Therefore, after a brief outline, we will focus on early
306 development and studies that have investigated the relation between early GF and the
307 diagnosis of ASD.

308 Several studies suggest that gaze cueing is intact in children with ASD (Chawarska,
309 Klin, & Volkmar, 2003; Kylliäinen & Hietanen, 2004; Swettenham, Condie, Campbell,
310 Milne, & Coleman, 2003), whereas a substantial minority suggest otherwise (for an
311 exhaustive review, see Nation & Penny, 2008). Many studies have shown that children with
312 ASD perform less GF than typically developing children (Chawarska et al., 2003; Falck-
313 Ytter, Fernell, Hedvall, Hofsten, & Gillberg, 2012; Leekam, Baron-Cohen, Perrett, Milders,
314 & Brown, 1997; Thorup, Kleberg, & Falck-Ytter, 2017), but quite a few have reported
315 similar performances (Falck-Ytter, Carlström, & Johansson, 2015; Freeth, Chapman, Ropar,
316 & Mitchell, 2010; Leekam, Hunnisett, & Moore, 1998). Some findings (Leekam, López, &
317 Moore, 2000; Mundy et al., 1994) suggest that a GF impairment may be most prominent
318 early in development or in autistic children with lower mental age. Although it remains
319 unclear to what extent GF is affected in ASD, different theories have been proposed to
320 explain the impairment, including a diminished interest in faces and eyes (Chevallier, Kohls,
321 Troiani, Brodtkin, & Schultz, 2012); avoidance of eyes (Hadjikhani et al., 2017; but see
322 Kylliäinen et al., 2012); impaired eye-gaze direction detection (Forgeot d’Arc et al., 2017);
323 and reinforcement learning differences (Triesch, Teuscher, Deák, & Carlson, 2006).

324 **Do GF Atypicalities in Infancy Signal Risk for Later Emerging Autism?**

325 Because ASD has a relatively strong genetic component (Messinger et al., 2015) and
326 is rarely diagnosed before the age of 2-3 years (Boyd, Odom, Humphreys, & Sam, 2010),
327 focusing on infant siblings of diagnosed children has proven effective for studying early

328 development. A number of studies have shown that infants at high familial risk differ from
329 control infants at low risk in terms of early GF (Cassel et al., 2007; Ibañez, Grantz, &
330 Messinger, 2013; Thorup et al., 2016; but see Goldberg et al., 2005; Yirmiya et al., 2006, for
331 negative results). However, to answer the question of whether early GF differences can
332 predict later diagnostic status, we must consider studies that followed infants until the age of
333 eligibility for diagnostic assessment. Most of them report some association between altered
334 early GF and later ASD (Bedford et al., 2012; Landa, Holman, & Garrett-Mayer, 2007;
335 Rozga et al., 2011; Sullivan et al., 2007; Yoder, Stone, Walden, & Malesa, 2009), but several
336 studies have not reported an association (Chawarska et al., 2014; Ibañez et al., 2013; Macari
337 et al., 2012). Direct comparison between studies is difficult because major methodological
338 differences exist. However, the level of saliency of gaze cues (e.g., the model silently looking
339 at the target, or vocalizing and pointing) may be important: infants at risk for ASD perform
340 better when multiple cues are used in combination, whereas low-risk infants respond equally
341 well to more subtle cues (Presmanes, Walden, Stone, & Yoder, 2007; Thorup et al., 2016).
342 Only one of the studies with outcome data assessed for differences in terms of cue saliency,
343 and it showed that 14-month-olds with later atypical outcomes performed comparably to
344 typically developing children in response to a model who used pointing, but worse in
345 response to a gaze shift/head turn only. These findings by Sullivan et al. (2007) offer some
346 support for the hypothesis that a lower sensitivity to gaze cues may be associated with later
347 ASD. However, data from typical infants aged 15-21 months show that additional cues, such
348 as pointing and verbalization, increase not only GF but also attention to the social partner
349 (Deák, Walden, Yale Kaiser, & Lewis, 2008); therefore, it may not be excluded that infants
350 with ASD require additional motivation to focus on the source of gaze cues.

351 In contrast to most studies that assessed GF during live interaction with an
352 experimenter, Bedford et al. (2012) used eye tracking and pre-recorded stimuli and did not

353 detect any differences in terms of accuracy. Their findings suggested that in a highly
354 controlled setting, infants with later ASD might be able to follow gaze to the same extent as
355 infants without later ASD. However, the authors also discovered that infants with later ASD
356 spent less time looking at the target compared to typically developing infants. This result may
357 suggest that in ASD other people's gaze is taken less into account – a finding that has
358 recently received some support from studies of older children with ASD (Falck-Ytter, 2015;
359 Thorup et al., 2016). In conclusion, although there is evidence for some association between
360 early GF alterations and later ASD, its nature and specificity needs further investigation.

361 **Theoretical Perspectives on the Developmental Origins of GF**

362 As we previously introduced, questions about how GF emerges have become
363 intrinsically connected with theories that attempt to explain the function of GF in infancy.
364 Hypotheses explaining GF emergence can be classified as either domain-general or domain-
365 specific. In the first case, a traditional domain-general hypothesis holds that cognitive
366 maturation and perceptual refinement determine the development of GF. For example,
367 Butterworth and Jarrett (1991) suggested that GF might emerge as a multi-step progression of
368 the infant's ability to connect another's line of sight to distant targets. Those authors
369 hypothesized that imprecise decoding of direction early in life might prevent joint attention –
370 or the shared attention between two individuals toward an object – which often involves GF.
371 According to that theory, spatial attention is required for visual joint attention. Another
372 perspective holds that GF arises as part of reinforcement learning; this process has been a
373 prominent contender for the domain general hypothesis (Corkum & Moore, 1998), and we
374 will discuss it further below in the Reward Learning section. In the second case, a traditional
375 domain-specific hypothesis assumes that infants are equipped with specific forms of
376 knowledge that independently influence the development of cognitive skills. One author who

377 has assumed independent, specific neurocognitive systems as premises of GF emergence is
378 Baron-Cohen (1995). He argued that infants are equipped with a neurocognitive system
379 called the *eye-direction detector*, whose primary purpose is to gain information about
380 another's direction of sight and that allows rudimentary GF. In addition, he predicted the
381 existence of a *sharing attention module* – a related but independent neurocognitive system
382 that becomes active afterwards and that allows infants to interpret eye direction in terms of a
383 mental state representation. Even though this view works conveniently as an example of a
384 domain-specific account, the perspective does not cover the multifaceted phenomenology of
385 GF because its application is limited at most to specific contexts, where GF and shared
386 attention occur independently (e.g., when sharing attention with a person wearing sunglasses)
387 without even providing an explanation of the underlying mechanism.

388 As outlined above, the development of GF is complex and appears to involve many
389 more factors than those described in these early theories. In the following sections, we
390 attempt to highlight the theoretical perspectives and debates that relate to the emergence of
391 GF during the first year of life.

392 **Dynamic systems approach**

393 A number of authors have proposed that GF development could be viewed as a
394 dynamic system (Mundy, Sullivan, & Mastergeorge, 2009, p. 11; Triesch et al., 2006, p. 128).
395 According to this perspective, behavior emerges through the spontaneous organization of
396 processes within the individual, her behavior, and the environment in which she acts (Kelso,
397 2000; Smith & Thelen, 2003). In the beginning of life, a certain degree of behavioral
398 organization exists. The introduction of a new condition within the environment (e.g., the
399 social environment of the infant) or within the infant (e.g., physical development and growth)
400 may initiate a transition from one state of equilibrium or behavior (e.g., fixating on a social
401 partner's face without GF) to another (e.g., shifting the gaze from a social partner's face to

402 the object of her attention, i.e., GF). According to dynamic systems theories, development
403 often takes different paths, with variations among infants and children in both the rate of
404 development and the outcome. These variations arise because of small changes in the
405 variables that interact to create a dynamic system (Kelso, 2000). Therefore, a pre-defined
406 pathway of development is not expected, and GF development may constitute a dynamic
407 process that is controlled by multiple factors (e.g., social- and infant-related factors, as
408 outlined above). Consequently, this process is not exclusively based on a dedicated eye-
409 centered mechanism, as demonstrated by studies showing that infants tend to establish shared
410 attention to objects by following the hands of the caregivers in addition to their gaze (Yu &
411 Smith, 2013). The dynamic systems approach highlights the variability of GF and the
412 flexibility of its expression. However, conducting experimental tests that critically evaluate
413 this approach has been difficult because few potential outcomes can be used to disprove the
414 theory.

415 **Theories that capitalize on specific (socio-)cognitive processes**

416 Another set of theories about GF focuses on the infant's motivation in other people as
417 a basis for GF development. These theories argue that social interest serves as a motivation
418 for infants to follow another's gaze. The *Natural Pedagogy* theory, proposed by Gergely and
419 Csibra (2013), suggests that beginning from at least 6 months of age, infants pick up
420 ostensive cues (i.e., a direct gaze, infant-directed speech, and contingent actions) from adults;
421 these cues inform the infant that their interaction partner aims to transfer knowledge to her.
422 The authors argue that the process does not rely on an infant's own repertoire of actions,
423 experiences, or mental representations, to understand others (Csibra & Gergely, 2006). Here
424 GF is seen as a way for the infant to understand what the adult is referring to, making the
425 infant an active partner in a pedagogical context. For example, by fixating on the same object
426 as the adult, infants may hear a new word and learn that the word relates to a specific object

427 (Mattos & Hinzen, 2015; for more information, see the section on Language). According to
428 this perspective, in infancy, GF will occur only following ostensive cues (Senju & Csibra,
429 2008) because learning is the primary motivation for GF.

430 A second perspective was provided by Meltzoff (2008). According to his *Like-Me*
431 hypothesis, infants possess an innate representational system based on the concept that others
432 are similar to themselves (Brooks & Meltzoff, 2014; Meltzoff, 2008). In this view, infants
433 possess insights about their own and others' actions, and they employ a combination of innate
434 abilities (Meltzoff & Moore, 1977) and the mirror neuron system (Rizzolatti & Craighero,
435 2004) to map the actions of others onto their own motor representations; this ability allows
436 infants to understand others as themselves (Meltzoff, 2007). This framework is not specific to
437 GF, but it has provided a foundation for some related concepts, such as neonatal imitation
438 and goal understanding (Meltzoff, 2007). With respect to GF, it is assumed that once an
439 infant knows that she can gain insight into the source of a rattle by turning her head, she also
440 understands that a social partner can turn the head to gain insight into an object that is
441 important to him/her. Therefore, the infant may very well be motivated to follow another's
442 line of sight because she is aware that the adult changes gaze direction when a nearby object
443 is within sight. Eventually, the infant will accumulate knowledge about how eyesight works,
444 and this knowledge will refine the situations that induce the infant to follow gaze (i.e.,
445 beyond when the head is moving and only when the eyes are wide open; Meltzoff, 2008).

446 Each of these theories has been criticized, and it is unlikely that any of them can
447 capture GF in all its complexity. In general, Natural Pedagogy postulates the existence of a
448 genetic mechanism that underlies the adaptation of GF to the purpose of knowledge transfer,
449 but the authors Csibra and Gergely do not even conjecture about what this mechanism could
450 be and do not provide strong empirical evidence and a unified explanation of their specific
451 predictions. First, Natural Pedagogy claims that GF should occur only in young infants in

452 communicative contexts (Senju & Csibra, 2008). However, this claim has been questioned in
453 several studies (de Bordes, Cox, Hasselman, & Cillessen, 2013; Szufnarowska et al., 2014;
454 Gredebäck et al., 2018) demonstrating GF following after non-ostensive cues (Szufnarowska
455 et al., 2014), and in the absence of any attempt to communicate or draw infant's attention to
456 the actor shifting gaze (Gredebäck et al., 2018) at the age most relevant to the natural
457 pedagogy theory – 6 months. Furthermore, the receptivity of infants to the gaze of adults
458 might serve other important functions apart from transmission of knowledge, such as social
459 bonding (Heyes, 2016). Second, several examples indicate that the coordination of attention
460 and the transmission of knowledge can occur without GF, e.g., cultural contexts in which
461 infants are held on the laps or backs of caregivers, when infants have to naturally rely on
462 postural cues (Akhtar & Gernsbacher, 2008), and deaf and blind dyads in which caregivers
463 mostly communicate through physical contact (e.g., deaf parents use “tapping” on the infants
464 body as an ostensive cue; Akhtar & Gernsbacher, 2008).

465 The “like-me” hypothesis draws inferences from neonatal imitation, a controversial
466 phenomenon that has been at the heart of a debate from the very day of its publication, and
467 that has been revitalized in the last few years (Meltzoff et al., 2017; Oostenbroek et al.,
468 2016). Therefore, the available data are not sufficient to support the claim of an innate action-
469 representation capacity; yet, the role of accumulation of experience with eyesight is
470 somewhat more in line with the available evidence, and longitudinal investigations of the
471 continuity between gaze cueing and GF might provide support.

472 **Reward learning**

473 According to the perspective of reward learning, frequent engagement with persons –
474 usually, the caregivers – fuels a reward-based learning process, known as reinforcement
475 learning (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). In fact, infants enjoy
476 watching persons who show responses contingent to their behavior (Rennels & Kayl, 2017)

477 and objects that are visually salient (Gredebäck, Johnson, & von Hofsten, 2010). An infant
478 that voluntarily controls her attention rapidly discovers that she encounters attractive objects
479 more frequently by following the gaze of adults. This concept can be rephrased in operant
480 conditioning terms: infants are reinforced to follow the gaze of others because doing so often
481 leads to rewards. With time, the infant will form a stable tendency to follow the gaze of
482 others. Early studies tested and discarded the role of operant conditioning in the development
483 of GF. In particular, Corkum and Moore (1998) demonstrated that infants could not be
484 trained to orient to the direction opposite to another's gaze by offering a reward; however,
485 this involved 8-to-10-month-old infants that already had gained substantial experience with
486 GF (Triesch et al., 2006). More recently, a study demonstrated that infants engaged in a face-
487 to-face play interaction preferred to look at objects that the caregivers were handling (Deák,
488 Krasno, Triesch, Lewis, & Sepeta, 2014); the authors hypothesized that handling the object
489 constituted the reward value that in turn reinforced the response to other associated cues, such
490 as the gaze. However, determining the degree of involvement of operant conditioning in the
491 formation of GF remains problematic. In fact, three challenges exist.

492 First of all, reward learning is difficult to reconcile with the observation that the more
493 rewarding the targets are, the less the infants perform GF (see above: Properties of the target
494 objects). Secondly, as noted above, it has been pointed out that infants of blind parents, who
495 are unlikely to provide reinforcement for GF, follow gaze to the same extent as children of
496 sighted parents. Nonetheless, modern theorists that support a reward-based origin of GF do
497 not exclude the possibility that reinforcement may enhance an inborn predisposition (Triesch
498 et al., 2006). Least, but not least, it appears that GF is more prominent during interactions
499 with strangers than in interactions with mothers. Gredebäck et al. (2010) argued that this
500 outcome was not compatible with formal models of reinforcement learning, such as the
501 model described by Rescorla and Wagner (1972). According to this theory, learned responses

502 should be strongest in the presence of the stimuli one was trained on (i.e., parents) and
503 weaken as a function of the level of familiarity of the social partner (i.e., GF should occur
504 less frequently in interactions with unfamiliar adults). In response, Deak et al. (2014) argued
505 that strangers might be more salient and thus might provide a stronger reward signal and
506 elicit more GF – however, reinforcement would require multiple exposures. Each of these
507 challenges might be countered by refinements of the reinforcement learning account, but
508 together they form a rather large barrier that might prove challenging to overcome.

509 **A way forward**

510 As a whole, studies demonstrate that the rudimentary ability to follow gaze is present
511 in during the first year of life, and progressively changes and improves across the first year.
512 Eventually, the infant perceives and reacts to the higher-level cues provided by, and
513 properties of, social partners and relies less on the low-level attributes of a stimulus.
514 However, this common ground is fraught with dissent about the mechanisms that give rise to
515 these changes and what processes might subtend the transition. Furthermore, the available
516 evidence draws a complex picture of GF development that neither confirms nor rejects any of
517 the current state-of-art theoretical proposals. A fresh view on the findings, with the aim to
518 integrate complementary accounts, rather than selecting one single explanation, may offer a
519 way forward from the impasse.

520 One novel suggestion is here referred to as the *Perceptual Narrowing Account of GF*
521 *Emergence*. This account suggests that the refinement of GF may be seen as a perceptual
522 narrowing process – e.g., from following motion in the shape of head and gaze cues,
523 irrespective of eyes status and primarily focused on temporal contingency – to exclusively
524 following the gaze of a human with open eyes, even if the head points to another direction.

525 The cornerstones of the Perceptual Narrowing idea are 1) that infants are born with a
526 form of attentional bias that enables a preference for speech sounds and faces that is rather

527 broad (i.e., extended to monkey calls and inverted face-like displays); and 2) that the initial
528 sensitiveness progressively refines through individualized experiences (e.g., hearing a
529 particular voice and seeing the faces of a specific group of people, and eventually showing a
530 preference/being more skilled at discriminating familiar items than unfamiliar ones).
531 Correspondingly, newborns and young infants show an attentive bias to the direction of gaze
532 expressed as shifts in head and eye-gaze direction (Farroni, Johnson, & Csibra, 2004): this
533 initial sensitivity is rather broad for the first months, as a broad range of stimuli and agents
534 implement early GF based on low-level cues, as highlighted by numerous authors (Deák,
535 2015; Farroni et al., 2004; Gredebäck et al., 2018; Meltzoff & Brooks, 2007; Moore et al.,
536 1997). Progressively, the close interaction with the environment fine tunes neural networks
537 dedicated to GF that might undergo a perceptual narrowing similar to what has been
538 demonstrated for face perception and language (Maurer & Werker, 2014): infants become
539 attuned to specific directional cues that they are mostly exposed to and start to ignore non-
540 specific but salient cues (e.g., eye-gaze shift versus head motion).

541 Some data could be reconnected to an explanation of GF development in terms of
542 Perceptual Narrowing. First, infants show a progressive calibration to the most familiar
543 stimulus presentation – an adult shifting her gaze with open eyes – that overtakes the initial
544 bias to follow any shift of the head. In fact, from 10 months, infants follow the others' gaze
545 only if the social partner has open eyes. This stimulus is not only naturally common but also
546 reinforced by the concurrent preference for faces with open eyes (Farroni, Csibra, Simion, &
547 Johnson, 2002). This process could explain the delay of GF adaptation to obstruction with
548 artificial elements, such as blindfolds, as a comparable experience is more rare in infants'
549 everyday context.

550 Another set of studies found that young infants follow the gaze of strangers more than
551 they follow the gaze of caregivers. It should be noted that this stranger paradox has been

552 observed when infants are quite young (below age 6 months; e.g. Gredebäck et al., 2010;
553 Striano & Bertin, 2005). At this stage, GF is not yet specialized and might be regulated by
554 general processes, such as a transient novelty preference (Theuring et al., 2007). Moreover,
555 we do not know whether older infants show a reverted preference for caregivers over
556 strangers, as the only longitudinal study with strangers and mothers involved infants at a
557 maximum age of 8 months (Gredebäck et al., 2010).

558 With regard to non-human agents (e.g., a green oval without facial features in Johnson
559 et al., 2008) providing a contingent response to the infants' action, they are effective in
560 directing an infant's attention with their body mass between age 12 and 15 months
561 (Deligianni, Senju, Gergely, & Csibra, 2011; Johnson et al., 2008; Johnson, Slaughter, &
562 Carey, 1998). Similarly to the above points, a specialization towards the most common shape
563 of the social partners might overtake the initial sensitiveness to contingent actions provided
564 by these agents. The age-dependent enhancement of the fixation duration (Senju et al., 2015)
565 and neural processing of GF targets (Reid, Striano, Kaufman, & Johnson, 2004) might be
566 related to the perceptual specialization of GF as well: we observe a similar phenomenon with
567 the enhanced attention and neural processing associated with familiar faces and speech
568 sounds of the native language (Maurer & Werker, 2014). Notably, the increase in attention is
569 mediated by early experiences in both contexts (e.g., children of blind parents do not increase
570 their attention on the target of GF, Senju et al., 2015; and children reared in multicultural
571 environments do not show a visual preference for own-race faces, Maurer & Werker, 2014).

572 Crucially, this proposal is in line with the *attenuation/reorganization* view of Maurer
573 and Werker (2014), because the highly dynamical character of this specialization entails that
574 higher level skills do not suppress early GF: rather, it predicts that new and old skills
575 integrate and that basic skills, such as sensitivity to motion and contingency, may be at work
576 when no other cue is provided.

577 One additional aspect of this view is that it reconciles many of the accounts outlined
578 in the previous paragraph. In fact, both operant conditioning and social motivation might
579 provide contributions to GF emergence that are directly related to the infant's own
580 experience, their social cognition (Gredebäck & Daum, 2015), and theory of mind (Shepherd,
581 2010). In particular, an attentive bias and social motivation may provide the context where
582 GF emerges and where reinforcement learning enables progressive fine-tuning. Ostensive
583 cues may highlight situations where important information is provided to the infant and
584 where skills like GF are implemented, yet they are by no means limited to a restricted set of
585 actions (e.g., eye contact and infant-directed speech) but rather incidental to the interaction
586 routine of the infant and her social partners. This process advances at the pace of neural
587 maturation and individual experiences and might be best described as a dynamic system that
588 settles on the stable state of GF, expressed in a large array of physical and social contexts but
589 with the magnitude of response shifting with the multitude of variables that contribute to the
590 emerging system (see the "Development of GF in the First Year" section). This view
591 incorporates the long-term associations among GF, language, attention and/or
592 neurodevelopmental disorders, and diagnoses such as ASD as a primary source for GF
593 understanding. In fact, infants at risk of ASD and/or with atypical outcome are misaligned on
594 several of these domains, with a lower sensitivity to eye-gaze cues, need of additional
595 motivation to focus on the social partner and less time spent fixating the target object (see the
596 "Do GF Atypicalities in Infancy Signal Risk for Later Emerging Autism?" section). These
597 results suggest that, despite a rather intact ability in terms of GF accuracy, the long-term
598 process involving neural maturation and learning might be disrupted – future research should
599 focus on these domains with an emphasis on the longitudinal changes before and after the
600 onset of the symptoms.

601 Obviously, this explanation needs further specifications and proofs. Few longitudinal
602 studies exist, and more are needed especially to target the onset of GF between 4 and 6
603 months of age and gaze cueing even earlier. The use of a range of stimuli according to the
604 factors listed above (e.g., manipulating the aspects of the infant's social partner and the
605 context in which GF occurs) would be highly valuable for testing this. Furthermore,
606 longitudinal studies that relate these early abilities with concurrent temperament and
607 attentional factors as well as with long-term factors associated with GF, such as language
608 development and emotional regulation, might inform the relationship between narrowing,
609 functional outcomes and neurodevelopmental disorders.

610 **Conclusions**

611 In the past decade, we have gained detailed knowledge about factors that influence
612 GF in the first year of life. Evidence has shown that infants, in addition to a passive
613 alignment to an adult's attention, can also master the use of gaze in various situations.

614 Recent studies indicate that GF is more flexible than previously assumed by early
615 mechanistic theories (e.g., Baron-Cohen, 1995). For instance, in addition to following gaze,
616 infants also monitor many other aspects of adults' actions, such as hand actions. Moreover,
617 GF in infancy is intimately connected with factors related to the infant's characteristics (e.g.,
618 temperament), non-social phenomena (e.g., the saliency of objects), and the social context of
619 the infant (e.g., the presence of ostensive or attention-grabbing cues).

620 In the previous paragraphs, we mentioned that eye-tracking has extended researchers'
621 ability to unravel the rich social world of infants. Moreover, with future technological
622 advancements, which are on the rise, including Near Infrared Spectroscopy (Scholkmann et
623 al., 2014), source localization of EEG (Reynolds & Richards, 2009), pupil dilation (Laeng,
624 Sirois, & Gredeback, 2012), and home recordings (Meyer, Decamp, Hard, Baldwin, & Roy,

625 2010), the future of GF research appears to be even more exciting. Together with studies on
626 the influences of genetics and the environment (Emde et al., 1992), these methods could
627 provide a rich understanding of the variability in GF using a multitude of measures, from
628 behavioral to neurodevelopmental markers. Only with these techniques will the field be in a
629 good position to home in on the development of GF and the mechanisms involved.

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