The Developmental Origins of Gaze-Following in Human Infants

Teresa Del Bianco*[1,2]

Terje Falck-Ytter[3, 4]

Emilia Thorup[3]

Gustaf Gredebäck[3]

[1] Department of Psychology and Cognitive Science, University of Trento

[2] Centre for Brain and Cognitive Development, Department of Psychological Sciences, Birkbeck University of London

[3] Uppsala Child and Babylab, Department of Psychology, Uppsala University

[4] Center of Neurodevelopmental Disorders (KIND), Karolinska Institutet

* Corresponding author.

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

Phone: +44 020 7631 0764

Email: t.delbianco@bbk.ac.uk

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Abstract

During the first year of life, infants develop the capacity to follow the gaze of others. This behaviour allows sharing attention and facilitates language acquisition and cognitive development. This article reviews studies that investigated gaze-following before 12 months of age in typically developing infants and discusses current theoretical perspectives on early GF. Recent research has revealed that early GF is highly dependent on situational constraints and individual characteristics, but theories that describe the underlying mechanisms have partly failed to consider this complexity. We propose a novel framework termed the *perceptual narrowing account of GF* that may have the potential to integrate existing theoretical accounts.

Key words:

Gaze-following, infant development, shared attention

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

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

Aim of This Review

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

Defining and Measuring GF in Infants

GF is often measured in a context in which a model moves her head and eyes from a central location towards one of two targets placed symmetrically on either side of her. Alternatively, the model turns torso, head, and eyes (e.g., the *Early Social Communication Scale*; Morales, Mundy, Delgado, Yale, Neal, et al., 2000) – or the eyes only (Moore & Corkum, 1998). An experimenter (Moore & Corkum, 1998) or the infant's mother (Morales, Mundy, & Rojas, 1998) usually plays the role of the model. Each trial often includes an initial period of interaction to attract the infant's attention to the adult's face: it lasts a few seconds (Gredebäck, Theuring, Hauf, & Kenward, 2008) or continues until the infant is engaged (D'Entremont, Hains, & Muir, 1997). The targets are usually a pair of toys on a table (Gredebäck, Fikke, & Melinder, 2010) or posters (Mundy et al., 2007) and monitors (Deák, 2015).

GF is present when the infant shifts her gaze from the model's face to the object that the model looks at more often than would be expected by chance. The tendency to follow a gaze is often measured as a difference score, the number of trials with a correct gaze shift minus the number of trials with an incorrect gaze shift, and GF is defined as a difference score significantly above zero (Corkum & Moore, 1995). Other studies rely on the percentage of trials in which GF is observed, and include trials with no shifts in the total number of trials (Gredebäck et al., 2010). The infant's gaze shifts can be coded from videos (D'Entremont, 2000), by recording the infant's field of view with a head-mounted camera (Yoshida & Smith, 2008) or with eye tracking (Theuring, Gredebäck, & Hauf, 2007). Some studies also assess the degree to which infants look more towards the attended, than the unattended object (for instance, see Senju, Vernetti, Ganea et al., 2015; Theuring, Gredebäck, & Hauf, 2007; Thorup, Kleberg, & Falck-Ytter, 2017). Regarding the specific definition of the behavior being used to produce the GF cue, it depends on the body part that the model used to turn: some authors oppose the use of GF when head and eyes are shifted together because the response to this action might involve motion-cueing (Deak, 2015). Nonetheless, the majority of studies addressing GF development during the first year involve a model shifting head and eyes congruently. Therefore, while using the term GF for simplicity and assuming that the model moved head and eyes together, throughout the review, we will specify only when relevant whether the study involved head and eyes together or the eyes alone. Beyond this controversy, in these contexts, the infant's overt gaze shift is considered to be motivated by the direction of the adult's gaze (Zuberbühler, 2008) and not reflexively triggered by the appearance of targets as in attentive cueing paradigms (Frischen, Bayliss, & Tipper, 2007).

Development of GF in the First Year

Before GF: the development of gaze cueing

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

Development of spontaneous GF

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

GF during the first year of life is not simply a response to any-and-all shifts of attention by a caregiver: the behavior depends on the properties of the elements that are readily available in an infant's close environment, the target object, and the interaction partners. Furthermore, infant-related factors that act as precursors and influence later correlates of GF are important to place GF into the typical (and atypical) developmental context. Support for each of these contextual and individual differences is addressed below.

Properties of the target objects

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

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

Factors related to social partners

The social partner can perform actions that increase the infant's tendency to follow the direction of gaze, including eye contact, infant-directed speech (Senju & Csibra, 2008), and attention-grabbing movements without social connotations, such as head-shaking (Szufnarowska, Rohlfing, Fawcett, & Gredebäck, 2014). The identity of the person performing the gaze cue can also influence GF. In a longitudinal study, Gredebäck and colleagues (2010) reported that GF is expressed earlier during live interactions with a stranger than during interactions with the infant's mother. In this study, the infat's eye-movements were recorded with an eye-tracker while the infant interacted with either a female stranger (an experimenter) or her own mother (50% of the infants). The experimenter/the mother placed two toys next to them and were instructed to engage the infant and shift their head and eyes toward one of the two toys. Two measures of GF – the differential score and the percentage of correct gaze shifts on the total number of trials – revealed a consistent growth pattern between 4 and 6 months in the stranger condition, while GF remained at chance level in the mother condition up until 6 to 8 months. A previous longitudinal study (Striano & Bertin, 2005) showed similar results, even though the authors used a less structured paradigm (i.e., free-play with a strager/the infant's mother), coded the videos manually and operationalized GF with a slightly more restricting criteria (i.e., the infants had to look at the toy before engaging with the adult). Despite the methodological differences, this study found that infants from 5 to 9 months of age increased their tendency to follow gaze only during stranger–infant interactions. At the same time, event-related potentials studies demonstrate that in 4-month-olds who interact with their parents, relative to strangers, stronger positive slow wave responses are associated with enhanced attention to the target being attended to during GF (Hoehl et al., 2012). Even though based on a small set of studies, we may hypothesize that novelty (associated with strangers) might strengthen the focus of attention on others and their gaze and that familiarity (e.g., the mother) might strengthen the focus of attention on the objects targeted by the gaze.

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

Factors Related to the Infant: Precursors and Later Correlates

Responsiveness to eye-gaze

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

Individual differences

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

Language

Longitudinal studies have demonstrated that GF is associated with language acquisition and can predict word comprehension and vocabulary (Morales et al., 2000; Mundy et al., 2007; Tenenbaum et al., 2015). In the period between 6 and 12 months of age, when infants happen to gaze at a face, the frequency of GF is correlated with the amount of attention dedicated to the mouth, an index of ongoing language acquisition (Tenenbaum et al., 2015). GF and language acquisition appear to go hand in hand; indeed, the infant's GF between 6 and 18 months of age could predict receptive and expressive language outcomes at 1-2 years of age (Morales et al., 2000; Mundy et al., 2007; Tenenbaum et al., 2015). In particular, infants who are better at GF develop a larger vocabulary between age 14 and 30 months than infants with less GF ability (Brooks & Meltzoff, 2005; Markus, Mundy, Morales, Delgado, & Yale, 2000; Mundy et al., 2007; Tenenbaum et al., 2015). One study showed that the combination of GF and an infant's vocalizations interacted to predict word comprehension at 14–18 months of age (Brooks & Meltzoff, 2005). Those authors hypothesized that at an age when infants start to grasp the referential meaning of gaze, vocalizations may represent a "preverbal effort" to communicate actively with the social partner behaviour that may play a role in the progression of linguistic skills (Brooks & Meltzoff, 2005). However, to validate this idea, studies are needed that target the meaning of this preverbal effort.

Sustained attention

The development of spontaneous GF before 6 months of age and long response latencies of GF in the first year of life that we mentioned before (D'Entremont, 2000) might be explained by the initially immature cortical frontal areas and executive functions (Canfield & Kirkham, 2001): one interesting aspect of executive function is that sharing attention through GF may contribute to maturation. Apart from increasing the time spent fixating on a specific object that is being looked at (Brooks & Meltzoff, 2005; Senju et al., 2015), bouts of joint attention between an infant and a parent, including GF, might prolong the infant's average fixation duration in general, a form of executive function also termed "sustained attention" (Yu & Smith, 2016). According to Yu and Smith (2016), sustained attention may specifically increase as a function of the parent's responsiveness. This hypothesis is supported by data showing that at the end of the first year, GF is correlated with the duration of visual orienting (Morales et al., 2000) and longitudinally predicts self-regulatory behavior (Vaughan Van Hecke et al., 2012) – suggesting that both phenomena may be partly mediated by the same process, i.e., executive function (Vaughan Van Hecke et al., 2012). However, to date, no study has investigated the direct relationship between GF, as it first emerges, and the self-regulation of attention and executive function.

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

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

ASD

ASD affects 1–1.5% of the population (Baird et al., 2006) and is characterized by impairments in social communication and interaction, restricted and repetitive behaviors and interests (American Psychiatric Association, 2013). The relation between GF and ASD is complex, and a full account of the area is out of the scope of this review (for an extensive review see Mundy, 2016). Therefore, after a brief outline, we will focus on early development and studies that have investigated the relation between early GF and the diagnosis of ASD.

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

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

Because ASD has a relatively strong genetic component (Messinger et al., 2015) and is rarely diagnosed before the age of 2-3 years (Boyd, Odom, Humphreys, & Sam, 2010), focusing on infant siblings of diagnosed children has proven effective for studying early development. A number of studies have shown that infants at high familial risk differ from control infants at low risk in terms of early GF (Cassel et al., 2007; Ibañez, Grantz, & Messinger, 2013; Thorup et al., 2016; but see Goldberg et al., 2005; Yirmiya et al., 2006, for negative results). However, to answer the question of whether early GF differences can predict later diagnostic status, we must consider studies that followed infants until the age of eligibility for diagnostic assessment. Most of them report some association between altered early GF and later ASD (Bedford et al., 2012; Landa, Holman, & Garrett-Mayer, 2007; Rozga et al., 2011; Sullivan et al., 2007; Yoder, Stone, Walden, & Malesa, 2009), but several studies have not reported an association (Chawarska et al., 2014; Ibañez et al., 2013; Macari et al., 2012). Direct comparison between studies is difficult because major methodological differences exist. However, the level of saliency of gaze cues (e.g., the model silently looking at the target, or vocalizing and pointing) may be important: infants at risk for ASD perform better when multiple cues are used in combination, whereas low-risk infants respond equally well to more subtle cues (Presmanes, Walden, Stone, & Yoder, 2007; Thorup et al., 2016). Only one of the studies with outcome data assessed for differences in terms of cue saliency, and it showed that 14-month-olds with later atypical outcomes performed comparably to typically developing children in response to a model who used pointing, but worse in response to a gaze shift/head turn only. These findings by Sullivan et al. (2007) offer some support for the hypothesis that a lower sensitivity to gaze cues may be associated with later ASD. However, data from typical infants aged 15-21 months show that additional cues, such as pointing and verbalization, increase not only GF but also attention to the social partner (Deák, Walden, Yale Kaiser, & Lewis, 2008); therefore, it may not be excluded that infants with ASD require additional motivation to focus on the source of gaze cues.

In contrast to most studies that assessed GF during live interaction with an experimenter, Bedford et al. (2012) used eye tracking and pre-recorded stimuli and did not detect any differences in terms of accuracy. Their findings suggested that in a highly controlled setting, infants with later ASD might be able to follow gaze to the same extent as infants without later ASD. However, the authors also discovered that infants with later ASD spent less time looking at the target compared to typically developing infants. This result may suggest that in ASD other people's gaze is taken less into account – a finding that has recently received some support from studies of older children with ASD (Falck-Ytter, 2015; Thorup et al., 2016). In conclusion, although there is evidence for some association between early GF alterations and later ASD, its nature and specificity needs further investigation.

Theoretical Perspectives on the Developmental Origins of GF

As we previously introduced, questions about how GF emerges have become intrinsically connected with theories that attempt to explain the function of GF in infancy. Hypotheses explaining GF emergence can be classified as either domain-general or domain-specific. In the first case, a traditional domain-general hypothesis holds that cognitive maturation and perceptual refinement determine the development of GF. For example, Butterworth and Jarrett (1991) suggested that GF might emerge as a multi-step progression of the infant's ability to connect another's line of sight to distant targets. Those authors hypothesized that imprecise decoding of direction early in life might prevent joint attention – or the shared attention between two individuals toward an object – which often involves GF. According to that theory, spatial attention is required for visual joint attention. Another perspective holds that GF arises as part of reinforcement learning; this process has been a prominent contender for the domain general hypothesis (Corkum & Moore, 1998), and we will discuss it further below in the Reward Learning section. In the second case, a traditional domain-specific hypothesis assumes that infants are equipped with specific forms of knowledge that independently influence the development of cognitive skills. One author who has assumed independent, specific neurocognitive systems as premises of GF emergence is Baron-Cohen (1995). He argued that infants are equipped with a neurocognitive system called the *eye-direction detector*, whose primary purpose is to gain information about another's direction of sight and that allows rudimentary GF. In addition, he predicted the existence of a *sharing attention module* – a related but independent neurocognitive system that becomes active afterwards and that allows infants to interpret eye direction in terms of a mental state representation. Even though this view works conveniently as an example of a domain-specific account, the perspective does not cover the multifaceted phenomenology of GF because its application is limited at most to specific contexts, where GF and shared attention occur independently (e.g., when sharing attention with a person wearing sunglasses) without even providing an explanation of the underlying mechanism.

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

Dynamic systems approach

A number of authors have proposed that GF development could be viewed as a dynamic system (Mundy, Sullivan, & Mastergeorge, 2009, p. 11; Triesch et al., 2006, p. 128). According to this perspective, behavior emerges through the spontaneous organization of processes within the individual, her behavior, and the environment in which she acts (Kelso, 2000; Smith & Thelen, 2003). In the beginning of life, a certain degree of behavioral organization exists. The introduction of a new condition within the environment (e.g., the social environment of the infant) or within the infant (e.g., physical development and growth) may initiate a transition from one state of equilibrium or behavior (e.g., fixating on a social partner's face without GF) to another (e.g., shifting the gaze from a social partner's face to the object of her attention, i.e., GF). According to dynamic systems theories, development often takes different paths, with variations among infants and children in both the rate of development and the outcome. These variations arise because of small changes in the variables that interact to create a dynamic system (Kelso, 2000). Therefore, a pre-defined pathway of development is not expected, and GF development may constitute a dynamic process that is controlled by multiple factors (e.g., social- and infant-related factors, as outlined above). Consequently, this process is not exclusively based on a dedicated eye-centered mechanism, as demonstrated by studies showing that infants tend to establish shared attention to objects by following the hands of the caregivers in addition to their gaze (Yu & Smith, 2013). The dynamic systems approach highlights the variability of GF and the flexibility of its expression. However, conducting experimental tests that critically evaluate this approach has been difficult because few potential outcomes can be used to disprove the theory.

Theories that capitalize on specific (socio-)cognitive processes

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

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

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

Each of these theories has been criticized, and it is unlikely that any of them can capture GF in all its complexity. In general, Natural Pedagogy postulates the existence of a genetic mechanism that underlies the adaptation of GF to the purpose of knowledge transfer, but the authors Csibra and Gergely do not even conjecture about what this mechanism could be and do not provide strong empirical evidence and a unified explanation of their specific predictions. First, Natural Pedagogy claims that GF should occur only in young infants in communicative contexts (Senju & Csibra, 2008). However, this claim has been questioned in several studies (de Bordes, Cox, Hasselman, & Cillessen, 2013; Szufnarowska et al., 2014; Gredebäck et al., 2018) demonstrating GF following after non-ostensive cues (Szufnarowska et al., 2014), and in the absence of any attempt to communicate or draw infant's attention to the actor shifting gaze (Gredebäck et al., 2018) at the age most relevant to the natural pedagogy theory – 6 months. Furthermore, the receptivity of infants to the gaze of adults might serve other important functions apart from transmission of knowledge, such as social bonding (Heyes, 2016). Second, several examples indicate that the coordination of attention and the transmission of knowledge can occur without GF, e.g., cultural contexts in which infants are held on the laps or backs of caregivers, when infants have to naturally rely on postural cues (Akhtar & Gernsbacher, 2008), and deaf and blind dyads in which caregivers mostly communicate through physical contact (e.g., deaf parents use "tapping" on the infants body as an ostensive cue; Akhtar & Gernsbacher, 2008).

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

Reward learning

According to the perspective of reward learning, frequent engagement with persons – usually, the caregivers – fuels a reward-based learning process, known as reinforcement learning (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). In fact, infants enjoy watching persons who show responses contingent to their behavior (Rennels & Kayl, 2017) and objects that are visually salient (Gredebäck, Johnson, & von Hofsten, 2010). An infant that voluntarily controls her attention rapidly discovers that she encounters attractive objects more frequently by following the gaze of adults. This concept can be rephrased in operant conditioning terms: infants are reinforced to follow the gaze of others because doing so often leads to rewards. With time, the infant will form a stable tendency to follow the gaze of others. Early studies tested and discarded the role of operant conditioning in the development of GF. In particular, Corkum and Moore (1998) demonstrated that infants could not be trained to orient to the direction opposite to another's gaze by offering a reward; however, this involved 8-to-10-month-old infants that already had gained substantial experience with GF (Triesch et al., 2006). More recently, a study demonstrated that infants engaged in a face-to-face play interaction preferred to look at objects that the caregivers were handling (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014); the authors hypothesized that handling the object constituted the reward value that in turn reinforced the response to other associated cues, such as the gaze. However, determining the degree of involvement of operant conditioning in the formation of GF remains problematic. In fact, three challenges exist.

First of all, reward learning is difficult to reconcile with the observation that the more rewarding the targets are, the less the infants perform GF (see above: Properties of the target objects). Secondly, as noted above, it has been pointed out that infants of blind parents, who are unlikely to provide reinforcement for GF, follow gaze to the same extent as children of sighted parents. Nonetheless, modern theorists that support a reward-based origin of GF do not exclude the possibility that reinforcement may enhance an inborn predisposition (Triesch et al., 2006). Least, but not least, it appears that GF is more prominent during interactions with strangers than in interactions with mothers. Gredebäck et al. (2010) argued that this outcome was not compatible with formal models of reinforcement learning, such as the model described by Rescorla and Wagner (1972). According to this theory, learned responses should be strongest in the presence of the stimuli one was trained on (i.e., parents) and weaken as a function of the level of familiarity of the social partner (i.e., GF should occur less frequently in interactions with unfamiliar adults). In response, Deak et al. (2014) argued that strangers might be more salient and thus might provide a stronger reward signal and elicit more GF – however, reinforcement would require multiple exposures. Each of these challengs might be countered by refinements of the reinforcement learning account, but together they form a rather large barrier that might prove challenging to overcome.

A way forward

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

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

The cornerstones of the Perceptual Narrowing idea are 1) that infants are born with a form of attentional bias that enables a preference for speech sounds and faces that is rather broad (i.e., extended to monkey calls and inverted face-like displays); and 2) that the initial sensitiveness progressively refines through individualized experiences (e.g., hearing a particular voice and seeing the faces of a specific group of people, and eventually showing a preference/being more skilled at discriminating familiar items than unfamiliar ones). Correspondingly, newborns and young infants show an attentive bias to the direction of gaze expressed as shifts in head and eye-gaze direction (Farroni, Johnson, & Csibra, 2004): this initial sensitivity is rather broad for the first months, as a broad range of stimuli and agents implement early GF based on low-level cues, as highlighted by numerous authors (Deák, 2015; Farroni et al., 2004; Gredebäck et al., 2018; Meltzoff & Brooks, 2007; Moore et al., 1997). Progressively, the close interaction with the environment fine tunes neural networks dedicated to GF that might undergo a perceptual narrowing similar to what has been demonstrated for face perception and language (Maurer & Werker, 2014): infants become attuned to specific directional cues that they are mostly exposed to and start to ignore non-specific but salient cues (e.g., eye-gaze shift versus head motion).

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

Another set of studies found that young infants follow the gaze of strangers more than they follow the gaze of caregivers. It should be noted that this stranger paradox has been observed when infants are quite young (below age 6 months; e.g. Gredebäck et al., 2010; Striano & Bertin, 2005). At this stage, GF is not yet specialized and might be regulated by general processes, such as a transient novelty preference (Theuring et al., 2007). Moreover, we do not know whether older infants show a reverted preference for caregivers over strangers, as the only longitudinal study with strangers and mothers involved infants at a maximum age of 8 months (Gredebäck et al., 2010).

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

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

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

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

Conclusions

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

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

In the previous paragraphs, we mentioned that eye-tracking has extended researchers' ability to unravel the rich social world of infants. Moreover, with future technological advancements, which are on the rise, including Near Infrared Spectroscopy (Scholkmann et al., 2014), source localization of EEG (Reynolds & Richards, 2009), pupil dilation (Laeng, Sirois, & Gredeback, 2012), and home recordings (Meyer, Decamp, Hard, Baldwin, & Roy, 2010), the future of GF research appears to be even more exciting. Together with studies on the influences of genetics and the environment (Emde et al., 1992), these methods could provide a rich understanding of the variability in GF using a multitude of measures, from behavioral to neurodevelopmental markers. Only with these techniques will the field be in a good position to home in on the development of GF and the mechanisms involved.

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