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Developmentally distinct gaze processing systems: Luminance versus geometric cues

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ABSTRACT

Two experiments examined how the different cues to gaze direction contribute to children's abilities to follow and make explicit judgements about gaze. In each study participants were shown blurred images of faces containing only luminance cues to gaze direction, line-drawn images containing only fine-grained detail supporting a geometric analysis of gaze direction, and unmanipulated images. In Experiment 1a, 2- and 3-year olds showed gaze-cued orienting of attention in response to unmanipulated and blurred faces, but not line-drawn faces. Adult participants showed cueing effects to line drawn faces as well as the other two types of face cue in Experiment 1b. In Experiment 2, 2-year-olds were poor at judging towards which of four objects blurred and line-drawn faces were gazing, whereas 3- and 4-year-olds performed above chance with these faces. All age groups performed above chance with unmanipulated images. These findings are consistent with an early-developing luminance-based mechanism, which supports gaze following, but which cannot initially support explicit judgements, and a later-developing mechanism, additionally using geometric cues in the eye, which supports explicit judgements about gaze.

1. Introduction

Knowing what someone is attending to is one of the most fundamental 'theory of mind' abilities. Tracking attention is required to determine the content of more complex representational mental states such as knowledge or belief. Consequently, understanding of visual attention has been argued to be a precursor to understanding belief. As Gómez (1996) puts it, understanding eye direction is "an early and simple way to know what is in the other's mind, because the contents of the other's mind – the object looked at – is in front of the beholder's eyes" (p. 334). Researchers on infant gaze-following typically conceptualise infants' understanding in terms of representational mental states. For example, Butler, Caron, and Brooks (2000) suggest that following an adult's gaze direction indicates that children understand "that there is a psychological and attentional relation between adult and target". This view is consistent with recent findings of early sensitivity to others' false beliefs from late infancy (Clements & Perner, 1994; Onishi & Baillargeon, 2005; Southgate, Senju, & Csibra, 2007).

Gaze-following[1] ability may be present in rudimentary form early in infancy. Hood, Willen, and Driver (1998) found that 4-month-olds' attention could be cued by an image of a face executing a gaze shift to one side, without

[1] In this paper we use the term "gaze following" to denote either an overt shift of attention in the gazed-at direction or a covert shift of attention which does not involve a movement of the eyes. Covert deployment of attention is usually inferred by some performance benefit in responding to targets towards which another's gaze has recently been directed, relative to targets that have not been cued in this way.

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a concomitant head turn. This only occurred when the face vanished before target onset, suggesting limitations on infants' ability to shift their attention. Naturalistic following of shifts in eye-direction alone can be reliably demonstrated by the age of 18 months (Moore & Corkum, 1998).

However, while they are able to *follow* gaze from infancy, children cannot make *explicit judgements* about the same stimuli until the age of about 3 years. For example, Doherty and Anderson (1999) found that only a minority of 3-year-olds and not all 4-year-olds were capable of judging which of four widely separated objects a schematic face was looking at, or which of two schematic faces was apparently looking at them. This difficulty is not limited to schematic faces, but also occurs with photographs (Anderson & Doherty, 1997; Doherty, Anderson, & Howieson, 2009) and in live interaction with a real person (Doherty & Anderson, 1999). The problem was not simply one of failing to understand the task, as the same children who were unable to judge gaze direction were well above chance in judging at which of the four objects a person was pointing (Doherty & Anderson, 1999; Doherty et al., 2009) or gazing, if the head also pointed in that direction (Doherty & Anderson, 1999). These findings seem to challenge the view, summarised above, that gaze following gauges a relatively sophisticated understanding of a psychological relationship between gazer and target.

How is it that children who can follow gaze, and who can make explicit judgements about pointing or head-and-eye direction cannot make such judgements solely on the basis of eye direction? Here we investigate the possibility that this is because infants' gaze following and older children's gaze judgements involve different aspects of visual information about gaze direction: luminance cues and the geometrical properties of the eye.

Ando (2002) has proposed that these two sources of information may each contribute to the perception of gaze direction. For example, the relative luminance of the iris and sclera can yield a measure which is proportional to the angle of rotation of the eye in the head (see also Langton, Watt, & Bruce, 2000), while a geometrical analysis involving, say, the spatial location of the iris within the eye region can also provide a measure of eye rotation. The luminance mechanism is likely to be fast but coarse, the geometrical mechanism slower but more precise, through operating at a higher spatial resolution.

Our suggestion is that the gaze following ability of children up to 2 to 3 years of age is likely to be based predominantly on luminance information. Certainly this seems likely for gaze following in early infancy: four-month-olds' visual acuity is poor – around 40 times lower than that of a normal adult (de Heering et al., 2008) – which limits their ability to resolve the edge between the iris and sclera necessary for geometrical analysis of gaze direction; however, they *are* able to perceive contrast at very low spatial frequencies (Banks & Salapatek, 1978), which should allow them to use the gross luminance configuration of the eye in order to compute gaze direction.

Furthermore, we suggest that children's gaze perception continues to be dominated by luminance information until around 3 years of age when they start to be able to make explicit judgements about the objects of other people's gazes (Doherty et al., 2009). This ability is initially fragile, however: 3-year-olds cannot yet distinguish between gaze to targets separated by 10° or 15° of visual angle (Doherty et al., 2009). Development then proceeds gradually, not reaching adult levels of sensitivity until around 10 years of age (e.g., Vida & Maurer, 2012). This pattern of development, from very limited ability to make fine discriminations at 3 years and protracted gradual development thereafter, suggests children are acquiring a new skill. We suggest that this skill involves the use of precise geometric cues in the eye to compute gaze direction on the basis of which a verbal report can be given. If children were simply making the output of their existing luminance-based ability available to verbal report, we would expect a more rapid development of judgement precision.

In summary, the suggestion is that gaze-cued attention is initially based on gross luminance information about eye direction. On the other hand, explicit judgements, which children make from around 3 years of age, additionally rely on more precise information derived from assessing the spatial configuration of eye features.

These suggestions lead to two key predictions. First, the gaze-following abilities of 2- to 3-year-old children will be dominated by luminance cues in the eye. Gaze-following should therefore be impossible if the relevant luminance information is removed. Second, at around 3 years of age children will begin to use geometric cues in the eye in order to make explicit gaze judgements. We report three studies that test these predictions. In Experiment 1a we tested gaze-following in a sample of 2- and 3-year-old children, and adults in Experiment 1b. In Experiment 2 we examined explicit gaze judgement in samples of 2-, 3-, and 4-year-olds. In each study we presented three different types of face cue: normal greyscale photographs, which contain both gross luminance and geometrical cues; blurred versions of these faces which retain luminance cues to gaze direction but where the precise spatial locations of the relevant eye features are difficult to resolve; and line-drawn versions where the spatial locations of eye features are available (geometric cues), but gross luminance cues to gaze direction are removed.

2. Experiment 1a

In Experiments 1a and 1b we used a gaze-cued orienting procedure. Toddlers were asked to identify which of two children's TV characters appeared briefly on a computer. Prior to the character's appearance, a face appeared on the screen either gazing towards the location where the character was to appear (a cued trial) or gazing in the opposite direction (an uncued trial). Gaze-following was operationalized as increased accuracy identifying the character in cued versus uncued locations. The key manipulation concerned the availability of the two cues to gaze direction: face images contained only luminance cues (blurred faces), only geometric cues (line-drawn faces) or both cues (normal faces). We hypothesise that 2- to 3-year-olds only have the luminance mechanism available for analysing gaze direction. They should therefore show a normal gaze-following response to images containing luminance cues (the normal and blurred faces) but not to