



The maturation of eye movement behavior: Scene viewing characteristics in children and adults



Andrea Helo ^{a,b,*}, Sebastian Pannasch ^c, Louah Sirri ^a, Pia Rämä ^{a,d}

^a Laboratoire Psychologie de la Perception, Université Paris Descartes, Paris, France

^b Escuela de Fonoaudiología, Universidad de Chile, Santiago, Chile

^c Department of Psychology, Engineering Psychology and Applied Cognitive Research, Technische Universität Dresden, Germany

^d CNRS (UMR 8242), Paris, France

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ABSTRACT

While the close link between eye movements and visual attention has often been demonstrated, recently distinct attentional modes have been associated with specific eye movement patterns. The ambient mode—serving the localization of objects and dominating early scene inspection—is expressed by short fixations and large saccade amplitudes. The focal mode—associated with the identification of object details and dominating later stages of scene exploration—is indicated by longer fixations embedded in short saccades. The relationship between these processing modes and eye movement characteristics has so far only been examined in adults. While studies in children revealed a maturation of oculomotor behavior up to adolescence, developmental aspects of the processing modes are still unknown. Here we explored these mechanisms by comparing eye movements during the inspection of naturalistic scenes. Therefore, gaze behavior from adults and children in four different age groups (2, 4–6, 6–8, 8–10 years old) was examined. We found a general effect of age, revealing that with age fixation durations decrease and saccade amplitudes increase. However, in all age groups fixations were shorter and saccades were longer at the beginning of scene inspection but fixations became longer and saccades became shorter over time. While saliency influenced eye guidance in the two youngest groups over the full inspection period, for the older groups this influence was found only at the beginning of scene inspection. The results reveal indications for ambient and focal processing strategies for as early as 2 years of age.

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1. Introduction

Vision is an active process that requires the sampling of visual information from the environment. Highest visual quality is achieved only within a small region at the center of gaze. This foveal region covers about 2° of visual angle. Therefore, fast saccadic eye movements are necessary to bring new visual information into this foveal region. During saccades the visual processing is suppressed; it happens mainly during fixations, when the gaze is relatively stable (e.g., Findlay & Walker, 1999; Thiele et al., 2002; Volkman, 1986). Extracting relevant fragments from a scene therefore requires both, saccades as well as fixations. Saccades are necessary to bring the eyes to regions of interest and during

fixations the information will be processed. Based on these assumptions, the spatial location of an eye-fixation can also be understood as an indicator for the allocation of visual attention (Henderson, 2007; Tatler & Vincent, 2008).

Eye movement patterns during scene perception have been investigated extensively in adults (for reviews, see Martinez-Conde, Macknik, & Hubel, 2004; Rayner, 2009; Schütz, Braun, & Gegenfurtner, 2011). Much of the research efforts are devoted to processes of spatial target selection, i.e. where viewers tend to fixate within a scene and which factors modulate this selection. It has been proposed that information processing and scan patterns are influenced by the interaction between bottom-up and top-down factors (Henderson, 2003; Oliva, 2005; Torralba et al., 2006). Bottom-up processing is guided by low-level features of images, such as saliency (Itti & Koch, 2000; Tatler, Baddeley, & Gilchrist, 2005; Tatler & Vincent, 2008) whereas top-down processing is based on endogenous control, such as semantic schema knowledge, working memory and behavioral task demands (Castelano, Mack, & Henderson, 2009; Fischer et al., 2013; Mills, Hollingworth, & Dodd, 2011; Tatler & Vincent, 2008).

* Corresponding author. Address: Laboratoire Psychologie de la Perception (CNRS UMR 8242), Université Paris Descartes, 45, rue des Saints-Pères, 75006 Paris, France. Fax: +33 (0)1 42 86 33 22.

E-mail addresses: andrea.helo@parisdescartes.fr (A. Helo), sebastian.pannasch@tu-dresden.de (S. Pannasch), louah.sirri@gmail.com (L. Sirri), pia.rama@parisdescartes.fr (P. Rämä).

Over the time course of scene exploration viewing behavior is under various control: during early instances mainly bottom-up saliency aspects are relevant while later in time top-down control becomes more dominant (Castelhamo, Mack, & Henderson, 2009; Mills, Hollingworth, & Dodd, 2011; Tatler & Vincent, 2008). These processing characteristics have recently been related to the certain patterns of eye movements, demonstrating a relationship between saccade amplitude, fixation duration and the respective attention mode (Pannasch et al., 2008; Pannasch & Velichkovsky, 2009; Tatler & Vincent, 2008; Unema et al., 2005; Velichkovsky et al., 2002, 2005).

Attentional processing has often been distinguished into ambient and focal modes. The ambient mode is expressed by short fixations (<180 ms) followed by large amplitude saccades (>5°). A dominance of ambient processing has been found during the first 2 s of scene viewing (e.g. Pannasch & Velichkovsky, 2009; Pannasch et al., 2008; Unema et al., 2005; Velichkovsky et al., 2002, 2005). The focal mode appears beyond the first 2 s and is characterized by long fixations (>180 ms) surrounded by saccades of relatively short amplitudes (<5°) (Tatler & Vincent, 2008; Unema et al., 2005; Velichkovsky et al., 2002, 2005). While the ambient mode has been related to bottom-up processing, the focal mode seems rather associated with top-down processing. Using a variety of experimental conditions and images, Pannasch et al. (2008) found expressions of ambient and focal gaze behavior when contrasting the first 2 s (early phase) with the interval from 4 to 6 s (late phase) of scene exploration. Ambient processing seems to be related to the overall spatial orientation in a scene, whereas focal processing serves the identification of objects (Pannasch & Velichkovsky, 2009; Velichkovsky et al., 2002, 2005). For example, Velichkovsky et al. (2002) demonstrated that ambient fixations are related to the detection of hazardous events in a dynamic driving task, whereas focal fixations are more related to the identification of these events. A subsequent experiment using static images revealed better recognition performance for fragments inspected in focal mode in contrast to those that were explored by ambient fixations (Velichkovsky et al., 2005). Based on these findings, it was suggested that the ambient and focal processing modes may recruit two distinct visual pathways (Pannasch & Velichkovsky, 2009; Velichkovsky et al., 2002, 2005). Accordingly, ambient processing is related to dorsal pathway activity, including areas located in the dorsal occipital and parietal lobes, by rapidly transferring visual information of low spatial resolution. The dorsal pathway has been associated with the processing of spatial relations and motion direction thereby enabling the spatial exploration of the environment (Corbetta, Patel, & Shulman, 2008; Milner & Goodale, 2008). In contrast, the ventral pathway, including the temporo-parietal junction and the ventral frontal cortex, seems to be related to the detection of salient and behaviorally significant stimuli as well as to the processing of object representations (Corbetta, Patel, & Shulman, 2008; Milner & Goodale, 2008). Therefore, it has been linked to the focal mode. Behavioral as well as neuroanatomical aspects of the two processing modes have already been examined in adults but it is still unknown whether this dichotomy is already present early in life or whether it evolves throughout development.

The oculomotor behavior develops in several steps during early childhood and adolescence. The capability to fixate a target is acquired during the first few months of life (Chandna, 1991; Roucoux, Culee, & Roucoux, 1983) but more complex aspects of the fixation system, such as steadiness of fixations and cognitive control continues to develop until adolescence (Luna, Velanova, & Geier, 2008). For instance, when subjects between 4 and 15 years of age have to maintain a fixation on a target, fixation durations increase and the number of reflexive saccades decrease with age (Aring et al., 2007; Ygge et al., 2005). Furthermore, the ability to

maintain fixation when peripheral distractors appear increased from 8-years-olds to 10-years-olds, suggesting that cognitive control of fixation develops until the age of 10 (Paus, Babenko, & Radil, 1990).

Regarding the development of saccade control, parameters such as peak velocity, latency and accuracy have been investigated (reviewed in Luna, Velanova, & Geier, 2008). While some studies found no age specific differences for saccade velocity (e.g. Luna et al., 2004; Munoz et al., 1998), others reported an increase in saccade velocity from 3 to 14 years of age (Irving et al., 2006). Saccades were found to be shorter and less precise when comparing children with adults. However, these parameters tend to stabilize around the age of 10 years (Fioravanti et al., 1995; Irving et al., 2006; Munoz et al., 1998). Likewise, saccade latencies have been found to decrease until the age of 15 years (Fukushima, Hatta, & Fukushima, 2000; Irving et al., 2006; Klein & Foerster, 2001; Luna & Sweeney, 2004; Munoz et al., 1998). Furthermore, cognitive control of saccade execution, operationalized by the performance in pro- and anti-saccades tasks, reaches an adult-like performance level at around 10–12 years of age (Fukushima, Hatta, & Fukushima, 2000; Irving et al., 2009; Klein & Foerster, 2001). Taken together, most aspects of saccade control and fixation system continue to develop through childhood.

Developmental aspects of eye movement control have been investigated mainly with the use of artificial stimuli and tasks (for review, see Luna, Velanova, & Geier, 2008). Only few studies employed naturalistic stimuli or scene perception (Egami et al., 2009; Vurpillot, 1968). In two studies, using visual comparative search, it was shown that children from 3 to 6 years old exhibit less exploratory eye movements than older children (6- to 14-years-olds); indicated by fewer and scarcely distributed fixations (Egami et al., 2009; Vurpillot, 1968). Related to processes of spatial target selection, a study conducted by Açıık et al. (2010) found a stronger influence of local image features on gaze allocation for children of 7–9 years of age than for adults. According to these results, during childhood the image exploration seems to be stronger affected by bottom-up features; top-down strategies become more influential later during maturation (Açıık et al., 2010). Other studies examining eye-movement patterns during scene viewing have tested atypically developed children (e.g. autistic and Williams syndrome) focusing mainly on fixation landing and scene comprehension (Fletcher-Watson et al., 2009; Riby & Hancock, 2008, 2009).

Recent reports revealed that the functionality of the dorsal and ventral pathways is developing during childhood (Braddick & Atkinson, 2011; Dekker et al., 2011; Gordon & McCulloch, 1999; Parrish et al., 2005). There are characteristic patterns in behavior (Braddick, Atkinson, & Wattam-Bell, 2003; Braddick & Atkinson, 2011; Gunn et al., 2002), suggesting that the ventral pathway matures earlier than the dorsal pathway (Armstrong, Maurer, & Lewis, 2009; Gunn et al., 2002; Klaver et al., 2008). Performance in the form coherence task—which is associated with the ventral pathway—children reach a similar level as adults with of 6–7 years of age. In contrast, performance in the motion coherence task—which is associated to the dorsal pathway—becomes comparable to the level of adults by the age of 10–11 years (Armstrong, Maurer, & Lewis, 2009; Gunn et al., 2002; Klaver et al., 2008). Moreover, atypically developed children (e.g. developmental hemiplegic, dyslexia and autism) show greater impairment in spatial tasks, suggesting that dorsal network is more vulnerable during development (Gunn et al., 2002; Koldewyn, Whitney, & Rivera, 2011; Ridder, Borsting, & Banton, 2001). These findings propose differences in the development of the two distinct visual pathways, but so far, these aspects were not linked to ambient and focal processing modes.

Studies on global and local processing of hierarchical visual forms have suggested a local processing bias in infants and younger children (e. g. Dukette & Stiles, 1996, 2001; Poirel et al.,

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