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The development of luminance- and texture-defined form perception during the school-aged years

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ABSTRACT

The objective of the present study was to assess the development of luminance- and texture-defined static form perception in school-aged children. This was done using an adapted Landolt-C technique where C-optotypes were defined by either luminance or texture information, the latter necessitating extra-striate neural processing to be perceived. Typically developing children were placed in one of 4 school-age groups (6, 8, 10 and 12-year olds); an adult group was also assessed. The contrast threshold for the correct identification of gap-opening-orientation for C-optotypes defined by either texture- or luminance-contrast was measured. All participants were presented with C-optotypes with gap-openings presented in one of 4 orientations (up, down, left or right). An adaptive staircase procedure was used to measure gap-opening-identification thresholds (minimum luminance- or texture-contrast modulation) for all three conditions and ages. As expected, gap-opening identification sensitivity (1/threshold) increased with age for all conditions. For both luminance-defined conditions, adult-like performance was manifested by 12 years of age. By comparison, at 12 years of age, the sensitivity to texture-defined C-optotypes was significantly lower than that of adults, having increased steadily from the age of 6 years. These results suggest that mechanisms underlying static form perception mature at different ages depending on the physical attribute defining the form. Luminance-defined form perception appears to reach adult-like levels (or plateau) earlier than for texture-defined information, suggesting that the development of mechanisms mediating higher-order form perception persist into adolescence.

1. Introduction

Situated within the emerging field of developmental cognitive neuroscience, charting the developmental trajectories across and within cognitive domains has become an important focus of research in recent years (Cornish & Wilding, 2010; Karmiloff-Smith, 1998; Scerif & Karmiloff-Smith, 2005). Among these domains, visual information processing represents an important function since it is intricately associated with the normal development of other cognitive abilities including language, attentional and motor skills (Berk, 2000). Our ability to efficiently differentiate, identify and recognize visual stimuli in our surroundings enables us to create a veridical internal representation of our external environment upon which we base our behavior. During typical development, the efficiency with which distinct image attributes (i.e., motion, form, color, etc.) are analyzed is contingent on the maturation of sensory (i.e., eye-related functioning) and/or neural systems involved in their processing.

The majority of studies assessing visual processing with age have operationally defined and evaluated development in terms of either ventral- or dorsal-stream functioning, since it is generally accepted that visual information processing can be defined by these two functionally segregated streams, associated with form and motion information processing, respectively (for a comprehensive review, see Braddick, Atkinson, & Wattam-Bell, 2003; Laycock, Crewther, & Crewther, 2006). In a comprehensive study by Parrish, Giaschi, Boden, and Dougherty (2005), the maturation of perceptual mechanisms mediating form and motion perception in school-aged children (3–12 years old) was assessed. Using a variety of tasks chosen to target either ventral- (i.e., form perception) or dorsal-stream (i.e., motion perception) functioning, Parrish et al. (2005) were able to define important critical periods of normal maturation for different types of visual processes (i.e., motion-defined form, 7–8 years; texture-defined form, 11–12 years; global texture, 3–4 years; global motion-coherence measure, 3–4 years; and global motion-D_{max} measure, 7–8 years). However, a stream-specific (i.e., dorsal stream) delay in maturation was not found, a negative finding

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explained by the authors as being the consequence of non-specific brain activation to form and motion stimuli used in their study (see Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000). Another possible reason for non-stream-specific findings in the Parrish et al. (2005) study is that it is difficult to assess both processing streams using stimuli that are equated for processing requirements (solicit both streams equally), a methodological issue that may potentially confound interpretations presented within the context of stream-specific dissociations (see Bertone, Mottron, Jelenic, and Faubert (2005) for complete discussion).

The most parsimonious manner to address this issue is to measure sensitivity to either static or dynamic stimuli (i.e., within-stream) while isolating and manipulating a single stimulus attribute that will solicit increasingly larger neural systems to resolve. This was the approach used in the present study where the development of static form perception was assessed in school-aged children while isolating and manipulating the physical attribute that defined the form's shape; boundaries defined by either a change in luminance or texture. Unlike the former, texture-defined (or second-order) information is defined by non-luminous spatial variations, necessarily requiring non-linear neural processing to be resolved (Cavanagh & Mather, 1989; Chubb & Sperling, 1988; Sperling, Chubb, Solomon, & Lu, 1994; Sutter, Sperling, & Chubb, 1995). The fact that we are able to perceive texture-defined information is of theoretical interest in that standard, linear mechanisms operating within the primary visual cortex are not able to passively process this class of information; additional non-linear neural processing is required before it can be extracted within extra-striate visual areas (Ashida, Lingnau, Wall, & Smith, 2007; Dumoulin, Baker, Hess, & Evans, 2003; Larsson, Landy, & Heeger, 2006; Nishida et al., 2003), as defined by filter-rectify-filter models (i.e., Baker, 1999).

Our group and others have successfully used luminance- and texture-defined gratings to define the developmental trajectories of a range of low-level perceptual abilities in both typically and atypically developing children using forced-choice identification paradigms (see studies below). Regarding typical development, it is generally well accepted that mechanisms involved in extracting texture-defined visual information mature at different rates compared to luminance-defined information, whether within static (i.e., Armstrong, Maurer, & Lewis, 2009; Bertone, Hanck, Cornish, & Faubert, 2008; Lewis, Kingdon, Ellemberg, & Maurer, 2007) or dynamic (i.e., Ellemberg et al., 2003; Ellemberg et al., 2005) domains. In addition, decreased sensitivity to texture-defined information has been demonstrated in several neurodevelopmental and pediatric patient populations where neural alteration is suspected (Bertone, Mottron, Jelenic, & Faubert, 2003, Bertone et al., 2005; Farzin, Whitney, Hagerman, & Rivera, 2008; Kogan et al., 2004; Thibault, Brosseau-Lachaine, Faubert, & Vital-Durand, 2007). In addition to delineating how low-level visuo-perceptual mechanisms develop with age, results from these studies have been used to define and dissociate condition-specific neural etiology underlying the perceptual processes across different patient populations (Bertone et al., in press).

The goal of the present study was to assess the development of luminance- and texture-defined form perception during the school-aged years, reflecting the maturation of both lower- and higher-level form processing mechanisms during typical development. To do so, a novel form perception task was used consisting of an adapted Landolt-C paradigm (Landolt, 1905), a procedure frequently used in the clinical evaluation of visual function. The traditional task consists of identifying the location of gap defining the orientation of a high-contrast C-optotype, while manipulating either its size or contrast. In the present study, the size of the C-optotypes was kept constant while the visibility of its form, defined by either luminance- or texture-contrast, was manipulated. This static task differs from other form tasks using similar optotypes in that participants are required to identify the orientation of the gap opening in the same Landolt-C optotype (up, down, left of right) rather than recognizing or naming a letter (i.e., Giaschi & Regan, 1997; Oruç, Landy, & Pelli, 2006; Regan & Hong, 1994), making it a more appropriate task for younger children, or children presenting developmental or language delay.

2. Methods

2.1. Participants

Participants were recruited through advertisements in a local family magazine in Montreal and from an already established database at the McGill Child Laboratory for Research and Education in Developmental Disorders, where the study was conducted. Ten typically developing participants were placed into each of 5 age groups ($N = 50$); (1) 6-year olds, 5.0–6.8 years, mean chronological age [CA] = 5.817 ± 0.639; (2) 8-year olds, 7.3–8.8 years, mean [CA] = 8.208 ± 0.595; (3) 10-year olds, 9.2–10.8 years, mean [CA] = 9.9 ± 0.617; (4) 12-year olds, 11.5–12.8 years, mean [CA] = 12.2 ± 0.47; and (5) adults (18–35 years), 19.1–35.0 years, mean [CA] = 23.3 ± 4.785.

In order to ensure typical development of each participant (except for adults), verbal mental age was assessed using the Peabody Picture Vocabulary Test (PPVT-R, Form L; Dunn & Dunn, 1997) for English-speaking participants, or the Échelle de Vocabulaire en Images Peabody (EVIP, Forme A; Dunn, Thériault-Whalen, & Dunn, 1993) for French-speaking participants. The PPVT and EVIP are standardized individually administered tests that consist of 175 vocabulary items of increasing difficulty used to assess the breadth of receptive language. PPVT/EVIP administration and scoring was completed before psychophysical testing and took approximately 15 min (on average) to complete. The verbal mental age of all participants fell well within or above norms for their age (6-year olds, mean verbal age [MA] = 6.709 ± 1.574); (8-year olds, mean [MA] = 9.058 ± 1.249); (10-year olds, mean [MA] = 12.333 ± 3.996); (12-year olds, mean [MA] = 16.042 ± 3.721).

For participants under 18 years of age, caregivers gave their consent for their child to take part in the study. None of the participants had a history of visual problems and all participants had normal or corrected-to-normal vision at the time of testing. Near and far vision was tested prior to testing for each participant (i.e., near point directional –E- and –C cards, Snellen letter sequence-A-new Logmar). Testing commenced after ethics approval was granted by the ethics committee at McGill University, consistent with the guidelines and tenets of the Declaration of Helsinki.

2.2. Apparatus and stimuli

Stimulus generation, presentation and data collection were controlled by a MacPro G4 computer using the VPIXX©(vpixx.com) graphics program. Stimuli were presented on a gamma-corrected 18-in. Viewsonic E90FB .25 CRT monitor (1280 × 1024 pixels), refreshed at a rate of 75 Hz. The mean luminance of the display was 50.0 cd/m^2, where L_{min} and L_{max} were 0.5 and 99.50 cd/m^2, respectively. Gamma correction (monitor linearization) was performed using a color look-up table within the VPIXX©program using a Minolta Chromameter. Gamma correction was assessed at regular intervals during testing in order to ensure proper monitor calibration.

Sensitivity was measured for three different optotypes; (1) luminance-defined C-optotypes, (2) texture-defined C-optotypes, and a (3) more traditional, control luminance-defined C-optotype constructed without the use of noise (similar to Chung, Li, & Levi, 2008 for letter stimuli). As with luminance- and texture-defined grating or bandpass stimuli produced by either adding or multiplying a modulating sinewave to visual noise (i.e., Bertone et al., 2008; Hutchinson & Ledgeway, 2006; Lewis et al., 2007), the luminance- and texture-defined optotypes in this study required greyscale noise to be constructed; a square display area containing static greyscale noise (subtending 8.6°) served as a background and was centered on the screen (see Fig. 1). For the luminance-defined condition, the optotypes's form was defined by the difference in average luminance between the noise defining the optotype's form and that of its surrounding background (see Fig. 1). For the texture-defined condition, the contrast of the noise defining the optotype's form was varied, resulting in a form defined by the difference in contrast of the noise defining its form and that of its background (average luminance of the form and its background equal). The luminance-defined, control condition was added to assess whether the presence of external noise differentially affected form perception with age.

For the luminance- and texture-defined conditions, the noise-filled background display area consisted of dots (1 pixel × 1 pixel, measuring ≈2″) with their individual luminance randomly assigned as a function of sin(x), where (x) ranged from 0 to 2π. The average luminance (L_B) and contrast (C_B) of the background noise was kept constant for all conditions (L_B = 50.0 cd/m^2; C_B set at 50% – or 0.5 – its maximal value); luminance- and texture-defined C-optotypes were presented within this background display area. For the control condition (no noise), the background display area was a uniform grey of 50.0 cd/m^2 (x = 0.2783, y = 0.3210 in CIE (Commission Internationale de l'Eclairage) color space). All C-optotypes had an outside and inside diameter of 5.0° and 3.0°, respectively, when viewed from 57 cm; the opening of the optotype was 1°.