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A test revealing the slow acquisition and the dorsal stream substrate of visuo-spatial perception

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ABSTRACT

We propose a battery of simple clinical tests to assess the development of elementary visuo-spatial perception. We postulate that most of the tasks we selected rely on the visual dorsal stream, although the dual-stream theory (Milner & Goodale, 1995) discards the role of the dorsal stream for visual perception. In order to test the contribution of this anatomical substrate in visuo-spatial perception, we evaluated the performance of two adult patients with acquired bilateral occipito-parietal (dorsal stream) damage. Additionally, the developmental evolution was assessed by testing 96 children from 4 to 12 years old (4 two-year age groups of 24 children). In order to determine the point at which children achieved adult performance, and to provide a control group for the two patients, we also tested a group of 14 healthy adults.

The results highlighted the necessity for age-dependent normative values: adult performance was achieved only at the age of 8 for length and size comparisons and at 12 for dot localisation. In contrast, the ability to judge angles and midlines did not reach adult performance even in the oldest group of children, suggesting further acquisition through adolescence.

Occipito-parietal lesions strongly and differentially affected elementary visuo-spatial tasks. In overall scores, the two adult patients were approximately at the level of 6-year olds, below the outlier limit of the adult group. They were on average within the adult interquartile range for processing length and size but clearly outside for the 4 other subtests (Angle, Midline, Position perception and Position selection).

As a whole, these data both shed light on the neuroanatomical bases of visuo-spatial perception and allow for age-specific comparisons in children with developmental disorders potentially linked to visuo-spatial and/or attentional defects.

1. Introduction

To our knowledge, no age-specific test is yet available to investigate the development of visuo-spatial processing. In children, most tests use pictures of familiar objects and a multi-choice design, thus simultaneously testing both object recognition and attentional selection. In adults, the Birmingham Object Recognition Battery (BORB: Riddoch & Humphreys, 1993) and the Visual Object and Space Perception (VOSP: Warrington & James, 1991) include subtests that are designed to specifically assess elementary visuo-spatial processing. Although designed and standardized for adults, the BORB and the VOSP are often used in children (e.g. Temple & Coleman, 2000; Jones & Tranel, 2001). The use of adult norms assumes implicitly that visuo-spatial capacities are acquired very early in childhood. However, there is scarce evidence for this in the literature: while visuo-manual reach-and-grasp abilities develop early during infancy (Clifton, Muir, Ashmead, & Clarkson, 1993; Sacrey, Karl, & Whishaw, 2012), perceptual integration skills develop later, particularly the processes involved in large-scale global perception (Rieth & Sireteanu, 1994; Kovács, 2000; Frostig, Lefever & Whittlesey, 1961; Braddick & Atkinson, 2007).

Note that this observation is often interpreted as showing evidence for the late maturation of the ventral visual stream (devoted to visual perception) as opposed to early maturation of the dorsal visual stream (devoted to action planning) (e.g., Kovacs, 2000), consistent with the dual stream model of vision (Milner & Goodale, 1995). However, it is not clear that perceptual integration skills with late functional maturation depend on a single (ventral stream) anatomical system. Instead, there is evidence of a major role of the dorsal visual system in visual perception via

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mechanisms of visual attention and visuo-spatial integration (e.g., Pisella et al., 2009; Pisella et al., 2012). The dichotomic assignment of visual perception to the ventral (occipito-temporal) visual stream and vision-for-action to the dorsal (occipito-parietal) visual stream (Milner & Goodale, 1995; Andersen & Cui, 2009; Andersen & Buneo, 2002) has been increasingly criticized and challenged (Colby & Goldberg, 1999; Bisley & Goldberg, 2010; McIntosh & Schenk, 2009; Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006; Pisella et al., 2009; Rossetti, Ota, Blangero, Vighetto, & Pisella, 2010; Schenk, Franz, & Bruno, 2011). Indeed, neuroimaging data has revealed that the involvement of the dorsal visual stream for visual object processing is not restricted within the context of motor actions (Faillenot, Decety, & Jeannerod, 1999; Konen & Kastner, 2008) and, in addition to specific visuo-manual deficits, lesions of the dorsal stream may have devastating consequences on the global perception of a visual scene (Balint, 1909, Ungerleider & Mishkin, 1982; review in Pisella, Ota, Vighetto, & Rossetti, 2008; Pisella et al., 2012). Large-scale global perceptual tasks may likely rely on the interplay between visuo-spatial integration (“Where”) and visual object processing (“What”), i.e. between the dorsal and the ventral stream, respectively. Accordingly, neuroimaging techniques have revealed that parietal dorsal stream areas show increasing activity associated with high-order visual perception during development (Klaver, Marcar, and Martin, 2011).

Given the lack of consensus on these important topics, the aims of the present study were to assess (1) the development of visuo-spatial perceptual skills and (2) the reliance of these skills on the dorsal visual stream. The present work consisted in selecting and adapting tests of visuo-spatial functions and subsequently testing children aged 4 to 12. In order to test the involvement of the dorsal visual stream in each subtest, the performance of two selected and extensively explored adults with acquired bilateral dorsal damage (patients IG and CF, Fig. 1A, see for example Pisella et al., 2000; Khan et al., 2005a; Khan et al., 2005b; McIntosh, et al., 2011; Granek et al., 2012) was also evaluated with the same material. A group of adults was also tested to provide a measure of the performance of healthy and mature visuo-spatial system.

2. Methods

2.1. Subjects

The study included 96 schoolchildren aged 4 to 12 years whose parents provided informed consent to participate. Exclusion criteria were: history of neurological disorders, premature birth, growth retardation, school-related problems, bilateral organic developmental amblyopia, and congenital or latent nystagmus. Children requiring glasses wore them during the test. The entire group of children was split into four two-year age-groups of 24 children each. The youngest group labelled [4–6], included children aged 4 years 0 months to 5 years 11 months; the other age groups were defined and labelled accordingly ([6–8], [8–10], [10–12]).

The study included 14 young adults (mean age: 23.8, SD: 4.5, range: 21 to 34 years, 10 females and 4 males) to provide baseline adult test scores and to investigate whether the abilities of children in the oldest age group were comparable to those of adults.

Two more adults with acquired bilateral occipito-parietal damage were included for a neuropsychological assessment of the involvement of the dorsal stream (occipital or parietal areas) in the subtests. Patient IG is a 37 year-old woman who suffered from an ischemic stroke 10 years earlier resulting in acute vasospastic angiopathy in the posterior cerebral arteries (established with an angiogram). Magnetic resonance imaging (T2 sequencing) revealed a bilateral lesion, fairly symmetrical in the two hemispheres, that was affecting the dorsal-lateral part of the posterior parietal and occipital cortex (Fig. 1A). Reconstruction of the lesion (Talairach, Tournoux Musolino, & Missir, 1988) indicated that, in the parietal lobes, it involved mainly the intraparietal and the parieto-occipital sulci with damage to Brodmann's area (BA) 7 in the superior parietal lobule, and also limited damage to the upper part of the angular gyrus (BA39) in the inferior parietal cortex. In the occipital lobes, it involved the superior occipital gyri (dorsal-lateral part of BAs 19 and 18). Patient CF is a right-handed 33-year-old male who suffered from a watershed posterior infarct 7 years earlier, resulting in distributed and asymmetrical bilateral lesions of occipital and parietal regions revealed by magnetic resonance imaging (see Fig. 1A). Reconstruction of the lesion (Talairach et al., 1988) indicated that it involved mainly the superior parietal lobules (BAs 2, 5 and 7) and the middle occipital gyri (BAs 18 and 19). A series of horizontal MRI slices can be found in Granek et al. (2012) for CF, and in Pisella et al. (2000) or Khan, Pisella, Rossetti, Vighetto, & Crawford (2005b) for IG. Behaviourally, patients IG and CF presented initially with clinical simultanagnosia and cortical blindness, respectively, but both recovered quickly. At the time of testing, both patients were characterised by chronic optic ataxia without clinical neglect. Interestingly, the lesion of patient IG is focal and the lesion of patient CF is distributed. As a consequence, their damage appear to be clearly different in the occipital lobe (superior occipital gyri, jointly to the posterior parietal cortex lesion in IG, and middle occipital gyri, separated from the posterior parietal cortex lesion in CF), but not in the posterior parietal cortex with a common damage to BA 7.

2.2. Subtest selection and adaptation

The test included subtests of pre-existing batteries (see below) that we re-designed to provide easier and more difficult items. This broadening of the range of difficulty enabled us to achieve the best sensitivity to age. For detailed item characteristics, see the supplementary information and test on-line.

Length and Size comparisons (subtests T1 and T2) were adapted from the BORB. They consisted in judging whether the two stimuli presented were of same or different magnitude. In contrast to the BORB, we presented each pair of stimuli on a separate sheet to avoid any possible complications involving attentional selection. We also increased the range of lengths and sizes differences. In the length comparison, we added a vertical dimension to the length comparison subtest to increase the number of comparisons to process in parallel: the 12 trials consisted of two sets of horizontal and vertical lines (e.g.: ____|_, ______|__) separated horizontally by 9 mm.

The Angle comparison task (subtest T3) involves the comparison of two crosses, thus the integration of four line orientations. The difference in orientation concerned the vertical or the horizontal line. The crosses were presented neither horizontally nor vertically, in such a manner that the comparison could not been made by comparing the positions/alignment of the line extremities. This subtest was derived from the BORB subtest which consisted of comparing the orientation of two single lines. Given that orientation-selective cells are present as early as in the primary visual area V1, the task was made more complicated to more specifically test higher levels of visual processing in the dorsal stream.

The test of **Midline localisation (subtest T4)** involved judging whether bisection marks of lines of 12 cm long are placed in the correct position. In human neuropsychology, line bisection is the classical test used to diagnose perceptual visual neglect, a disorder that commonly results from lesions in the inferior part of the posterior parietal cortex within the right hemisphere (Vallar & Perani, 1986; Mort et al., 2003). Neuroimaging data have confirmed that perceptual midline judgement is a specific function of the dorsal stream in the right hemisphere (Fink et al., 2000; Fierro et al., 2000). The pre-existing perceptual version of the line bisection test (perceptual midline judgement task) involved lines with bisection marks; participants are asked to judge whether these marks are left or right with respect to the true midline (Milner, Harvey, Roberts, & Forster, 1993; Bisiach, Ricci, Lualdi, & Colombo, 1998).

The **two Position subtests (T5 and T6)** were selected and adapted from the VOSP and consisted of comparing the positions of dots within a frame. These tasks are used clinically to diagnose dysfunction of the dorsal visual stream of processing (Rapport, Millis, & Bonello, 1998). Indeed, this ability of evaluating and comparing distances between object(s) and a landmark has been tested in monkey neuropsychology experiments to characterize the deficit consecutive to lesion of the dorsal visual stream (“Where” function, Ettlinger, 1990; Ungerleider & Mishkin, 1982). Subtest T6 was fairly similar to the VOSP: a single dot was presented in its frame and a second frame contained several coloured dot in which only was was matching the allocentric position of the single dot. The task was to give the colour of this dot. In subtest T5, we changed the VOSP in order to make a comparison task: two single dots were presented in their own frame (with direct alignment neither of the frame nor of the dot) and the task consisted in judging whether they were placed at the same location with respect to their frame.

The entire test is available on-line as supplementary document. The exact metrics of all the stimuli is also mentioned in a supplementary document on-line.

2.3. The testing conditions

The entire test included six subtests with 12 trials each. Subtests T1, T2, T3, and T5 relied on image-pair comparisons (or trials) that require a “same” or “different” response. Subtest T4 required a “midline” or “not midline” answer. Subtest T6 (position selection) was similar to T5 except that it required a multiple choice answer, i.e. the selection, among several coloured dashes in one image, of the dash that matches the position of a black dot on the paired image.

These subtests were presented in the order T1 to T6. The six “identical” and six “non-identical” image-pairs within each subtest were intermingled pseudo-randomly. The trials whose correct response is “different” (or “not midline” for T4) were presented in order of increasing difficulty. The twelve trials of T6 were presented in order of increasing number of distracters.