

# 1           **What does bilateral damage of the superior parietal lobes tells us about visual** 2                           **attention disorders in developmental dyslexia**

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4 S. Valdois<sup>1,2</sup>, D. Lassus-Sangosse<sup>3</sup>, M. Lallier<sup>4</sup>, O. Moreaud<sup>1,3</sup> et L. Pisella<sup>5</sup>

5  
6           1. CNRS, LPNC UMR 5105, 38040 Grenoble, France

7           2. Université Grenoble Alpes, LPNC, 38040, Grenoble, France

8           3. CMRR, Pôle Psychiatrie, Neurologie, Rééducation neurologique, CHU Grenoble-  
9           Alpes, France

10          4. Basque Center on Cognition, Brain and Language, 20009, San Sebastián, Spain

11          5. 1ImpAct – Lyon Neuroscience Research Center, Inserm U1028, CNRS UMR 5292,  
12          Bron, France,

## 13 14 15 **Abstract :**

16 Neuroimaging studies have identified the superior parietal lobules bilaterally as the neural  
17 substrates of reduced visual attention (VA) span in developmental dyslexia. It remains  
18 however unclear whether the VA span deficit and the deficits in temporal and spatial  
19 attention shifting also reported in dyslexic children reflect a unitary spatio-temporal deficit of  
20 attention - probably linked to general posterior parietal dysfunction- or the dysfunction of  
21 distinct attentional systems that relate to different neural substrates. We explored this issue  
22 by testing an adult patient, IG, with a specific damage of the bilateral superior parietal  
23 lobules after stroke, on tasks assessing the VA span as well as temporal and spatial attention  
24 shifting. IG demonstrated a very severe VA span deficit, but preserved temporal attention  
25 shifting. Exogenous spatial orientation shifting was spared but her performance was  
26 impaired in endogenous attention. The overall findings show that distinct sub-systems of  
27 visual attention can be dissociated within the parietal lobe, suggesting that different  
28 attentional systems associated with specific neural networks can be selectively impaired in  
29 developmental dyslexia.

30 Highlights: 3 to 5 on a separate file (85 characters max with blanks)

31  
32 Investigation of a patient with bilateral superior parietal lobe (SPL) damage  
33 Evidence for poor visual attention span but normal temporal attention shifting  
34 Normal exogenous but impaired endogenous spatial attention  
35 Involvement of the SPLs in specific visual attention subskills  
36 Different visual attention systems are involved in developmental dyslexia  
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40 Keywords: 6 Visual attention, brain damage, superior parietal lobule, developmental  
41 dyslexia, visual attention span, endogenous and exogenous spatial attention.  
42

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45

## 46 **1. Introduction**

1  
2 A variety of visual attention deficits has been reported in dyslexic individuals, supporting the  
3 visual attention account of developmental dyslexia (DD) (Vidyasagar & Pammer, 2010).  
4 More specifically, three main types of deficits have been reported: a visual attention (VA)  
5 span deficit (Bosse et al., 2007), a temporal attention shifting deficit (Hari & Renvall,  
6 2001) and a spatial attention orienting deficit (Facoetti et al., 2010). The Visual attention  
7 (VA) span deficit results in poor multi-element parallel processing due to a reduction of the  
8 visual attention resources available for processing. Deficits in exogenous and endogenous  
9 orienting of spatial attention are also reported, together with temporal attention shifting  
10 deficits that prevent the normal processing of rapidly presented stimulus sequences.  
11 These deficits follow from difficulties to engage or disengage attention during spatial  
12 processing or fast temporal processing. Although the existence of visual attention deficits in  
13 DD is now well established, some authors propose that they reflect the dysfunction of one  
14 single attentional system (Facoetti et al., 2006; Vidyasagar & Pammer, 2010) while others  
15 argue for two independent and functionally distinct, VA span and sluggish attentional  
16 shifting, systems that could be selectively impaired in DD (Lallier et al., 2010, 2012). Here,  
17 we will shed light on this debate from a neurobiological perspective. We reasoned that if  
18 attentional shifting and VA span deficits reflect the dysfunction of a single attention system,  
19 both skills should be implemented in the same neural network. Alternatively, two  
20 functionally distinct attentional systems should be implemented in two anatomically distinct  
21 neural networks.

22 There is no doubt that the parietal cortex plays a key role in attentional processing (Friedrich  
23 et al. 1998; Corbetta and Shulman 2002, 2011) and the sluggish attentional shifting skills of  
24 dyslexic individuals have been proposed to be underpinned by a dysfunction of this brain  
25 structure (Hari and Renvall, 2001). However, attentional shifting involves several different  
26 fronto-parietal sub-networks (Chica et al., 2013; Fan & Posner, 2002) that might be  
27 selectively affected in developmental dyslexia. From another line of research, bilateral  
28 superior parietal lobules have been identified as the cerebral correlates of the VA span, thus  
29 pointing to a dysfunction of a specific parietal area in relation to VA span deficits in DD  
30 (Lobier et al., 2012, 2014; Peyrin et al., 2011, 2012; Reilhac, 2013). Since the role of the  
31 SPLs in VA span performance is now well established, the aim of the current study was to  
32 determine whether the SPLs are further involved in the other visual attention disorders  
33 reported in developmental dyslexia. In order to do so, we will study the performance of a  
34 brain-damaged patient to determine whether (i) a bilateral SPL damage impacts both VA  
35 span and temporal/spatial attention shifting performance or (ii) a SPLs damage selectively  
36 impairs performance on VA span tasks without impacting temporal/spatial attention shifting.  
37 Evidence for (i) would support the unitary account of the visual attention deficit in  
38 developmental dyslexia, while evidence for (ii) would suggest that two distinct attentional  
39 systems independently contribute to reading acquisition and developmental dyslexia.

#### 40 41 *1.1. A VA span deficit in developmental dyslexia*

42  
43 Dyslexic individuals who show a VA span deficit (Bosse et al., 2007; Dubois et al., 2010;  
44 Germano et al., 2014; Zoubrinetzky et al., 2014, 2016) can only process a reduced number  
45 of distinct visual elements simultaneously due to limited visual attention capacity (Bogon et  
46 al., 2014 ; Lobier et al., 2013). Behaviourally, the deficit is highlighted using tasks of letter

1 report in which a multi-consonant string is briefly and centrally presented on a computer  
2 screen and subjects are required to orally report either all the consonant names (global  
3 report) or the name of a single cued consonant (partial report). Some dyslexic children  
4 exhibit impaired performance on these tasks despite preserved fast single letter  
5 identification. However, the deficit is not specific to letter-strings since similar poor  
6 performance is observed when using digits instead of letters within strings (Valdois et al.,  
7 2012). Importantly, children with poor performance in global and partial letter reports are  
8 similarly impaired in categorization tasks that do not require oral report and do not involve  
9 verbal material (Lobier et al., 2012a). Thus, these individuals show difficulties at multi-  
10 element parallel processing, regardless of the type of stimuli to be processed. In addition,  
11 Lassus-Sangosse et al. (2008) showed that the VA span deficit is specific to parallel  
12 processing: the dyslexic participants who were impaired at processing the 5-consonant  
13 strings in parallel could report as many letters as the controls when the five consonants  
14 were displayed sequentially, one at a time, at the center of the computer screen (see also  
15 Valdois et al., 2011). There is also evidence that the deficit is not specific to horizontal  
16 displays but extends to circular presentations (Dubois et al., 2010), which could explain why  
17 poor VA span also affects performance in non-linear visual search tasks (Lallier et al., 2013)  
18 and why VA span is higher in individuals who play action video games than in non-players  
19 (Antzaka et al., 2017). Overall, the available behavioural data points towards a visually-  
20 driven deficit that reflects a limitation in the amount of attentional resources available for  
21 multiple visual-element parallel processing.

22  
23 Neuroimaging studies report the hypoactivation of the bilateral SPLs in dyslexic individuals  
24 with a VA span deficit (Peyrin et al. 2011, 2012; Reilhac et al. 2013). Indeed, the SPLs were  
25 found activated under conditions of multi-element processing in normal readers (Lobier et  
26 al., 2012) and selectively underactivated in VA span-impaired dyslexic individuals (Lobier et  
27 al., 2014). Importantly, similar hypoactivation of the SPLs was found regardless of the  
28 alphanumeric or nonalphanumeric nature of the stimuli. These findings suggest that the  
29 SPLs are specifically involved in the simultaneous processing of multiple visual elements.  
30 Importantly, the link between VA span and the SPLs is specific. In the study of two  
31 contrasted cases, Peyrin et al. (2012) showed that underactivation of the SPLs during multi-  
32 element processing was only found in the dyslexic participant with a VA span  
33 deficit whereas the same brain regions were normally activated in the participant with a  
34 selective phonological deficit. This link is further supported by training studies, showing that  
35 the intensive use of a training program targetting VA span skills resulted in increased  
36 activation of the SPLs (Valdois et al., 2014). In sum, it is now well established that the SPLs  
37 are the cerebral correlates of the VA span.

38  
39 *1.2. A temporal attention shifting deficit in developmental dyslexia*  
40 Temporal attention shifting deficits have been reported in developmental dyslexia in tasks  
41 that require the rapid (10 stimuli per second) sequential processing of stimuli, such as  
42 stream segregation and attentional blink tasks (Hari & Renvall, 2001). Deficits on these  
43 tasks are interpreted as reflecting sluggish attentional shifting, a difficulty to automatically  
44 disengage the focus of attention from one stimulus to reengage it onto another stimulus  
45 appearing briefly after (Hari & Renvall, 2001).

1 In visual stream segregation tasks, two visual stimuli alternate between two different  
2 locations. When the two stimuli are temporally far apart, they are perceived as one stream,  
3 suggesting that attention covertly shifted from one location to the other. However, when the  
4 time interval between the two visual stimuli is shortened, they are perceived as two  
5 alternating flashing stimuli at distinct positions --two distinct streams—because the  
6 attentional focus can no longer shift fast enough. The stream segregation threshold  
7 corresponds to the time interval at which perception switches from one to two streams and  
8 indicates the fastest visual attentional shifting speed. Dyslexic children were reported to  
9 have higher visual stream segregation thresholds than normal readers, suggesting a  
10 reduced speed of automatic attentional shifting (Lallier et al., 2010a; see also Lallier et al.  
11 2009 for evidence on adult participants).

12 Results from studies using the attentional blink paradigm yielded similar conclusions. In the  
13 attentional blink paradigm, the visual stimuli presented in rapid succession are all displayed  
14 at the same spatial location. The participants are engaged in a dual task procedure which  
15 requires identifying a first target and then detecting a second target that is displayed at  
16 different time lags from the first target's presentation time. The probability to detect the  
17 second target decreases for the shortest lags -- participants are transiently blind to the  
18 target-- and progressively improves for longer lags. While normal readers fail to detect a  
19 second target that is presented within the first 500ms after the first target, the attentional  
20 blink is abnormally prolonged in dyslexic individuals (Buchholz & Davies, 2007; Hari et al.,  
21 1999; Lallier et al., 2010b; Visser et al., 2004).

22  
23 The parietal cortex has been proposed to be the neural substrate of the attentional blink  
24 deficit (Hari & Renvall, 2001; Hommel, Kessler, Schmitz, Gross, Akyürek, Shapiro &  
25 Schnitzler, 2006). In healthy individuals, Marois et al. (2000) identified the right parietal  
26 sulcus as the neural correlates of the attention system involved in the attentional blink  
27 paradigm, which is consistent with data from transcranial magnetic stimulation (Cooper,  
28 Humphreys, Hulleman, Praamstra & Georgeson, 2004). Shapiro et al. (2002) showed that  
29 the attentional blink more frequently followed from lesions of the temporo-parietal junction  
30 than of the SPLs in brain-damaged patients. The overall findings suggest that a right  
31 parietal sulcus dysfunction might account for visual sluggish attentional shifting skills in  
32 dyslexic individuals.

33

### 34 *1.3. A spatial attention shifting deficit in developmental dyslexia*

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36 Developmental dyslexia has also been associated with deficits in visuo-spatial attention. A  
37 deficit in orienting spatial attention was highlighted using the spatial cueing paradigm, a  
38 task originally designed by Posner (1980). In this paradigm, a target to be detected is  
39 preceded by a briefly presented cue that orient attention towards the target location (valid  
40 condition) or the opposite side (invalid condition). Valid cues trigger faster reaction times  
41 due to enhanced processing at the attended location. Invalid cues require to reallocate  
42 attention towards the target location, thus yielding slower reaction times. In exogenous  
43 cueing conditions, the cue is displayed in the periphery at the target location while it is  
44 centrally displayed in the endogenous condition and is predictive of the target location which  
45 appears in the periphery. Exogenous cueing involves automatic stimulus-driven attention

1 shifting towards the target location while endogenous cueing requires top-down voluntary  
2 attention.  
3 Both adults and children with developmental dyslexia show orienting difficulties on spatial  
4 cueing tasks (Brannan & Williams, 1987; Facoetti et al., 2006). Reduced sensitivity to  
5 exogenous cues was repeatedly reported in dyslexic individuals (Brannan & Williams, 1987;  
6 Facoetti et al., 2000, 2005, 2010a; Roach & Hogben, 2004) and spatial attention inefficient  
7 automatic orienting characterizes preliterate children with familial risk for developmental  
8 dyslexia (Facoetti et al., 2010b). Endogenous cueing was less systematically explored in  
9 developmental dyslexia and yielded more discrepant results. In some studies, a reduced  
10 cueing effect was reported in both the exogenous and the endogenous spatial cueing  
11 paradigms (Facoetti et al., 2006) but other studies reported normal cueing effect in the  
12 endogenous condition (Facoetti et al., 2000). In the studies where stimulus onset  
13 asynchrony (SOA) was manipulated, a reduced cueing effect was reported at short 100ms  
14 SOA but an amplified cueing effect at long 350ms SOA in the exogenous condition (Ruffino  
15 et al., 2014). In many studies, the spatial cueing deficit was found to only characterize a  
16 subset of dyslexic children who were severely impaired in pseudo-word reading accuracy  
17 (Facoetti et al., 2006, 2010a; Ruffino et al., 2010).

18  
19 Physiological studies of spatial attention orienting in healthy individuals have demonstrated  
20 the involvement of a bilateral network with core regions in parietal and frontal areas (Nobre  
21 et al., 1997; Wojciulik & Kanwisher, 1999; Yantis et al., 2002). Endogenous attention has  
22 been postulated to be implemented in a dorsal fronto-parietal network which includes the  
23 SPL bilaterally (Corbetta & Schulman, 2002; Shomstein & Behrmann, 2010; Chica et al.,  
24 2013). Exogenous attention would rely on a ventral fronto-parietal network, including the  
25 right temporo-parietal junction as a core region (Corbetta et al., 2000; Corbetta & Schulman,  
26 2002; Shomstein & Behrmann, 2010). However, the anatomical segregation of the two  
27 exogenous and endogenous attention systems is still debated (Chica et al., 2013). One  
28 cause of this ongoing debate is that the lesion of the ventral fronto-parietal network affects  
29 the dorsal one (Corbetta & Shulman, 2011); Conversely, a lesion of the SPL does not seem  
30 to affect the ventral fronto-parietal network (Gillebert et al. 2011 ; Shomstein & Behrmann,  
31 2010). Thus, the exploration of the exogenous and endogenous attention systems in a  
32 patient with bilateral SPL lesion is particularly relevant to distinguish the specific attentional  
33 processes in which the SPL is critically involved.

34  
35 *1.4. Purpose of the current study*  
36 The purpose of the current study is to contribute to the ongoing debate on attentional  
37 deficits in developmental dyslexia. Decades of behavioural research have provided  
38 evidence for the presence of VA span, temporal and spatial attention shifting deficits but  
39 their co-occurrence or independence in the dyslexic population remains an unresolved  
40 issue. Only a few studies have explored temporal and spatial attention in the same dyslexic  
41 participants. Ruffino et al. (2014) administered an exogenous spatial attention task and an  
42 original temporal attention task to groups of dyslexic children. Only the subset of dyslexic  
43 participants with the most severe pseudo-word reading accuracy deficit demonstrated  
44 impaired performance in visual attention. Temporal and spatial attention deficits were found  
45 to co-occur, suggesting that spatial exogenous and temporal attention may depend on the  
46 same functional system implemented by the same neural network. With respect to spatial

1 attention, current studies did not provide strong evidence for the independence or  
2 association of exogenous and endogenous attention deficits in developmental dyslexia.  
3 Some suggest deficits of the two spatial attention systems in developmental dyslexia  
4 (Facoetti et al., 2006) while others suggest a selective deficit of exogenous (stimulus-driven)  
5 attention (Facoetti et al., 2010b). Besides, evidence for a dissociation between VA span  
6 deficit and attention shifting deficits in developmental dyslexia is also scarce. Lallier et al.  
7 (2010c) administered tasks of attentional blink to a phonologically-impaired dyslexic  
8 participant and reported evidence for impaired temporal attention shifting despite preserved  
9 VA span abilities. Strong behavioural evidence is thus lacking in support or against the  
10 independence of the various visual attention disorders reported in developmental dyslexia.

11 At the neurobiological level, the spatial and temporal attention deficit in developmental  
12 dyslexia, as well as the VA span deficit are attributed to a parietal dysfunction (Hari &  
13 Renvall, 2001; Gori & Facoetti, 2014 ; Peyrin et al., 2011, 2012 ; Vidyasagar & Pammer,  
14 2010). In addition, there is strong evidence that the SPLs bilaterally are the neural  
15 substrates of the VA span deficit but the question remains whether these structures are also  
16 part of the neural substrates of temporal and spatial attention deficits in developmental  
17 dyslexia.

18 To address this issue, we will explore VA span, temporal attention and  
19 endogenous/exogenous spatial attention skills in a brain-damaged patient who suffered a  
20 bilateral SPL stroke. Based on previous evidence, this patient is expected to demonstrate a  
21 severe VA span deficit. Additional deficits on temporal and spatial attention tasks would be  
22 found if all these attentional components are implemented in the same parietal regions.  
23 Alternatively, a dissociation between poor VA span but preserved temporal and spatial  
24 attention in our patient would demonstrate that several attentional systems may  
25 independently contribute to developmental dyslexia. In addition, the performance of our  
26 patient should be impaired in condition of endogenous cueing if primarily dependent on the  
27 dorsal fronto-parietal network including the SPLs but preserved in exogenous cueing if  
28 implemented by the temporo-parietal junction of the ventral network (Chica et al., 2013;  
29 Shomstein et al. 2010).

30

## 31 **2. Case report**

32

33 IG is a right-handed 44 year-old woman who suffered from an ischemic stroke when she  
34 was 29. The lesion involved the whole area 7 and the intraparietal sulcus in both  
35 hemispheres, as well as the upper part of Brodmann's areas 19, 18 and 39 (corresponding  
36 to area PEG as defined by Eidelberg and Galaburda 1984) but spared area 40 and the  
37 tempo-parietal junction (see Figure 1a). Visual fields showed a partial right inferior  
38 homonymous quadrantanopia with temporal crescent sparing (Figure 1b), due to the  
39 subcortical damage of the optical radiations below the parietal cortex in the left hemisphere.  
40 Her visual acuity was normal (7/10 and 8/10 for the right and left eye respectively). She  
41 initially demonstrated a simultanagnosia and an impairment of online automatic visuo-motor  
42 guidance (i.e., bilateral optic ataxia) but never showed any hemineglect syndrome.

43 The present experiment was conducted 15 years after IG's ischemic stroke long after  
44 clinical simultanagnosia had regressed. IG was administered a general neuropsychological  
45 screening battery to explore the cognitive long-term effects of her brain damage. Table 1

1 summarizes her performance on tests of intellectual efficiency, executive and attentional  
2 functions, language and visual abilities.

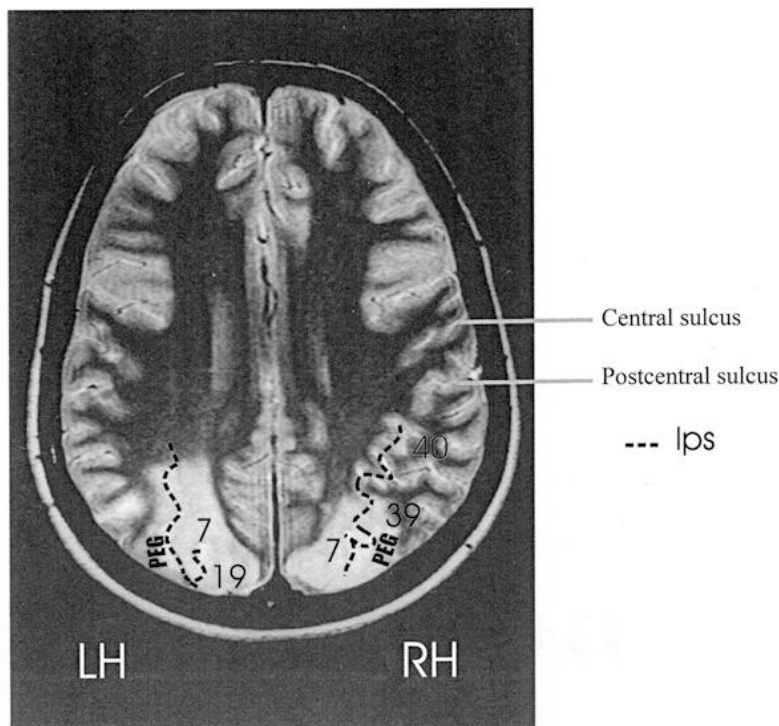
3  
4 As shown on Table 1, IG's verbal IQ was well within the normal range (IQ=110). She shows  
5 preserved executive functions (Wisconsin Card Sorting Test (WCST); Godefroy & Grefex,  
6 2008), good verbal short-term memory (WAIS IV forward and backward digit span) and  
7 good oral language abilities (Verbal IQ: Similitudes, Vocabulary, Informations; picture  
8 naming from the Becks Greco, Merck et al. (2011); Pseudo-word Repetition, alphabetic and  
9 semantic fluency). Her reading was functional and she did not complain for reading  
10 difficulties. However, she exhibited a reading age of 9 years 1 month on the Alouette  
11 Reading Test (Lefavrais, 1967), suggesting limited reading skills. Note that IG reported no  
12 history of reading or learning problems in childhood but she left school at the age of 16  
13 (after having completed a professional certificate of dressmaker). Her limited reading  
14 abilities may thus primarily reflect her socio-educational level but we cannot exclude some  
15 additional effect due to her ischemic accident.

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19 Figure 1: A-Horizontal section through IG's brain, visualised with structural MRI. B- Visual  
20 field perimetry for patient IG showing quadrantanopia in the right lower quadrant of the  
21 visual field of both eyes.

22  
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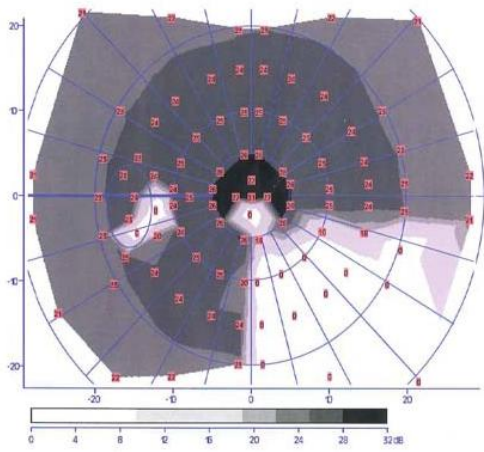
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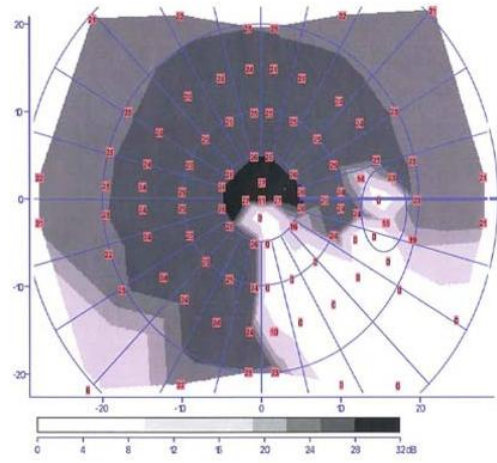
24  
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27

B

Left Eye



Right Eye



1



1

2 Table 1: IG general neuropsychological assessment (\*\* =  $p < .05$ )

TASKS	IG	Mean (SD) controls	t modified, Z-score or standard score (SS)/percentile
Intellectual efficiency Verbal IQ (WAIS IV)	110	100 (15)	$z=0.66 \sigma$
Executive functions			
Wisconsin Category	6	5.95 (0.22)	$t=0.22$
Wisconsin Errors	8	3.73 (2.66)	$t= -1.59$
Verbal Short term memory			
Forward digit span	7	6.2 (1.3)	$t= 0.61$ ; ou SS=11/19
Backward digit span	5	4.8 (1.4)	$t= 0.14$ ou SS =11/19
Oral Language			
Picture naming	40/40	39.5 (0.7)	$t=0.68$
Pseudo-word repetition	88/92	86.47 (2.62)	$t=0.58$
Semantic fluency	53	39.83 (7.78)	$t=1.68$
Alphabetic fluency	25	28.86 (5.55)	$t=-0.69$
Written Language			
Reading Age	9yrs 1mth		
Auditory attention			
PASAT	58		75°ct
Visual attention			
TMT A	105	42 (14)	$t= -4.47^{**}$
TMT B	208	66 (24)	$t=-5.88^{**}$
Bells Test			
score	34/35		(30-50)° ct
Time sec	222'		<5°ct**
Line bisection			
Long lines	+0.875cm		(50-60)°ct
Short lines	-0.05cm		(40-50)°ct
Visual processing (VOSP)			
Incomplete letters	17/20	Cut off : 17	=cut off
Dot counting	4/10	Cut off : 8	$z=-9.68\sigma^{**}$
Position discrimination	15/20	Cut off : 18	<cut off**
Single Letter identification threshold	33	33.3 (2 .25)	$z=- 0.13 \sigma$

3

4 Assessment of her attention abilities revealed good auditory but poor visual attention skills.  
5 She performed well within the normal range on the Paced Auditory Serial Addition Test  
6 (PASAT, Gronwall & Sampson, 1974; French adaptation: Mazza & Naegele, 2004), which  
7 suggests normal auditory attention and good calculation skills. In contrast, her poor  
8 performance on the two conditions of the Trail Making Test (TMT; Godefroy & Grefex, 2008)  
9 and on the Bells Test (Gauthier, Dehaut & Joanne, 1986) suggests poor visual attention  
10 processing abilities. Her performance on the latter task was characterized by good  
11 accuracy, showing preserved abilities to identify a specific target among visually similar  
12 distractors but at the cost of very long search time. In the same way, her very slow performance  
13 in condition A of the Trail Making Test --that requires connecting numbers in sequential order -- may  
14 primarily reflect a difficulty to locate the target numbers. Although performance on the TMT and  
15 Bells Test suggests impaired visual attention, IG's normal performance on the line bisection  
16 task (Schenkenberg et al. 1980) shows that her visual attention disorder is rather specific.  
17 IG's shows no sign of visual neglect either investigated through the line bisection task or  
18 through the very sensitive Bells Test. Actually, she never exhibited any hemineglect  
19 syndrome, even when her visual attention abilities were first explored just after her stroke  
20 when she was 29 (Pisella et al. 2000). The absence of hemineglect is well in line with her

1 very focal brain damage that spared the occipito-temporo-parietal junction. IG seems more  
2 specifically impaired when the task requires the processing of multiple elements as in the  
3 Bells test and TMT (but not in the line bisection task), a processing ability also involved in  
4 the dot counting and position discrimination subtests of the VOSP (Visual Object and Space  
5 Perception, Warrington & James, 1991) and in the incomplete letter subtest (Boucard &  
6 Humphreys, 1992). In contrast, her performance in single letter visual processing is  
7 remarkably preserved. In this task, single letters were randomly presented at the center of  
8 the screen for a short duration (varying from 33ms to 101 ms), immediately followed by a  
9 mask. IG was able to identify 90% single letters presented for only 33ms (and all the letters  
10 displayed for longer durations) a performance well within the norm of adult skilled readers  
11 (Valdois, Guinet & Embs, 2017).

### 12 **3. Experimental investigation**

13 IG was administered tasks of VA span, temporal and spatial attention shifting. The classical  
14 paradigms of global and partial report that require parallel processing of briefly presented 5-  
15 consonant strings were used to assess her VA span abilities (*Experiment 1*) together with  
16 an additional task of global report in which string-length and inter-letter spacing were varied  
17 (*Experiment 2*) to determine whether the deficit extended to shorter strings and reflected  
18 potential crowding effects. A sequential multi-letter processing task was further administered  
19 to ensure that the deficit highlighted in the VA span tasks was specific to simultaneous  
20 processing (*Experiment 3*). Temporal attention was assessed through visual tasks of stream  
21 segregation (*Experiment 4*) and attentional blink (*Experiment 5*) while exogenous  
22 (*Experiment 6*) and endogenous (*Experiment 7*) spatial cueing paradigms were used to  
23 assess IG's spatial attention skills.

24 In each experiment, IG's performance was compared to that of a control participant, ERB,  
25 and to control groups. ERB is a 46 year-old woman who reported no academic difficulty and  
26 was matched in age and school level with IG. She was right-handed and reported no  
27 medical or psychiatric illness. She exhibited a reading age of 14 years 3 months well within  
28 the normal range of young adults, suggesting that IG reading age (RA= 9;1) may have been  
29 affected by her brain damage. ERB was administered all the experimental tasks that were  
30 proposed to IG. Groups of RA-matched control participants or healthy young adults were  
31 further used for comparison. In particular, IG performance was compared to the  
32 performance of a group of reading age-matched (RA) controls in Experiment 1 and 2 to  
33 ensure that her poor performance on the tasks was not just the consequence of her poor  
34 reading level. The RA-matched control participants were administered the Alouette Reading  
35 Test to ensure that their reading level, as a group, was comparable to that of IG (all  
36  $p > 0.05$ ). The control participants attended school regularly and had never repeated a  
37 grade. None of them exhibited a reading disorder. Specific information on the control groups  
38 is provided at the beginning of each experiment.

39 In each experiment, modified t-tests were used to compare IG performance with ERB  
40 performance by referencing the difference to the control sample (Crawford, Garthwaite &  
41 Wood, 2010). This method allowed testing whether the difference between ERB and IG  
42 performance was greater than the difference observed among pairs of controls, in which  
43 case they were said to differ significantly. In each task, IG performance was further  
44 compared to the control group performance using modified t-tests, as recommended when

1 the size of the normative sample is small (Crawford et al., 2002). Moreover, this method is  
2 only minimally sensitive to departure from normal distribution (Crawford & Garthwaite,  
3 2006), which was required here as a lot of measured abilities were within the competence of  
4 most non-dyslexic control participants.

### 5 3.1. Visual attention span assessment

#### 6 3.1.1. Experiment 1: Global and Partial Report

7 *Participants:* IG, ERB and a RA-matched control group of 108 5th Grade children (Mean  
8 CA= 127.10; SD= 4.07) matched for reading age (Mean RA=120.89; SD= 20.06;  $p>.05$ ) with  
9 IG participated in Experiment 1.

10 *Stimuli:* Random five letter-strings (e.g., RHSDM) were built up from 10 consonants (B, P, T,  
11 F, L, M, D, S, R, H). The letters were presented in upper case (Geneva, 24) in black on a  
12 white background. The 5-consonant strings never matched the skeleton of a real word (e.g.,  
13 FLMBR for FLAMBER “burn”). The strings included no repeated letter, no frequent bigram  
14 (as BR or PL) and no meaningful substring (e.g., no frequent abbreviations as HLM in  
15 French). To control for potential crowding effects, the space between adjacent letters was  
16 increased (0.6 cm). The whole line subtended an angle of 5.4°. Twenty five-letter strings  
17 were successively presented in global report. Each letter was used ten times, twice in each  
18 position. Fifty random five-letter strings were displayed in partial report. Each letter occurred  
19 25 times and appeared five times in each position.

20 *Procedure:* At the beginning of each trial, a central fixation point was presented for 1000 ms  
21 followed by a blank screen for 50 ms. Then, a letter-string was displayed at the center of the  
22 screen for 200 ms, a duration long enough for an extended glimpse, yet too short for a  
23 useful eye movement (Figure 2a). In global report, a white screen was presented at the  
24 offset of the letter string and children had to report verbally as many letters as possible  
25 immediately after the disappearance of the string. In partial report, a vertical bar indicating  
26 the position of the letter to be reported was presented for 50 ms (1.1° below the target letter)  
27 at the offset of the letter-string (Figure 2b). Each letter was used as target once in each  
28 position. Participants were asked to report the cued letter only. In the two global and partial  
29 report tasks, the experimental trials were preceded of 10 training trials for which participants  
30 received feedback. No feedback was given during the experimental trials. The dependent  
31 measure was the mean number of letters accurately reported (identity not location) across  
32 the 20 trials (maximal score = 100) or the 50 trials for the global and partial report  
33 respectively. The partial report task was adapted to account for IG’s right quadrantanopia  
34 that interfered with the presentation of the vertical cue when presented below the target in  
35 the right visual field. The vertical bar was thus presented above instead of below the target  
36 letter in both the left and right visual fields.

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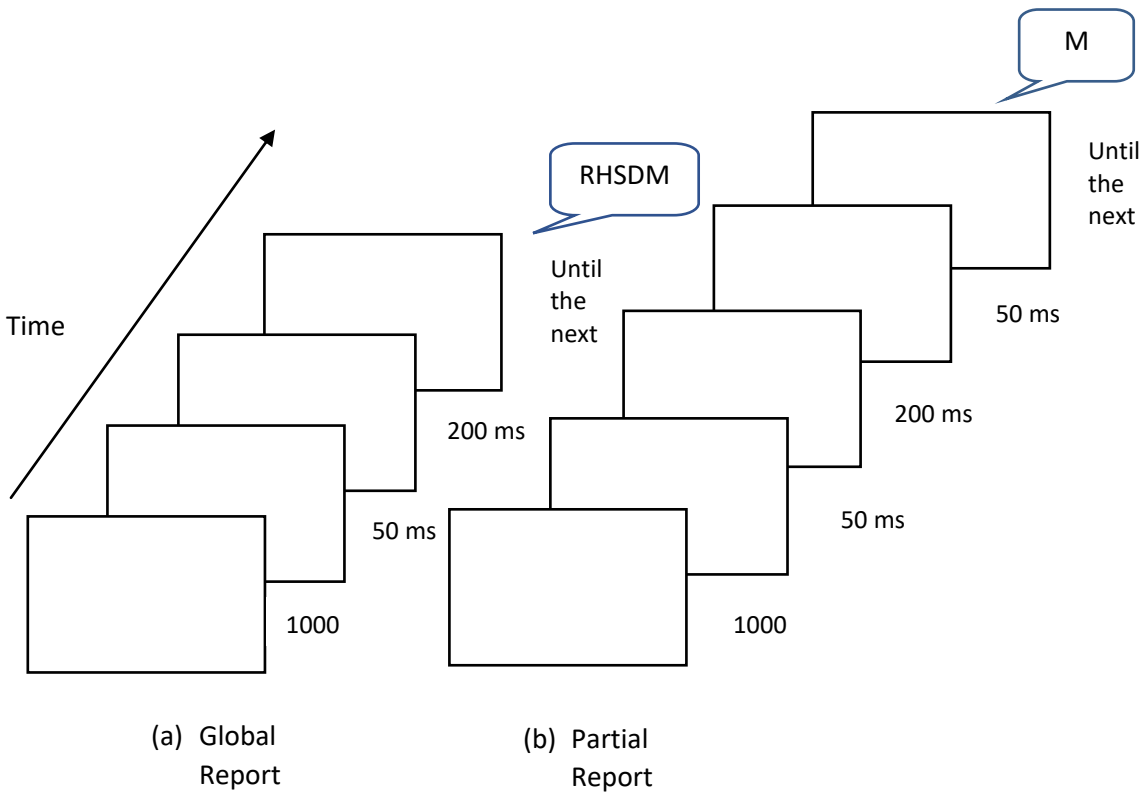
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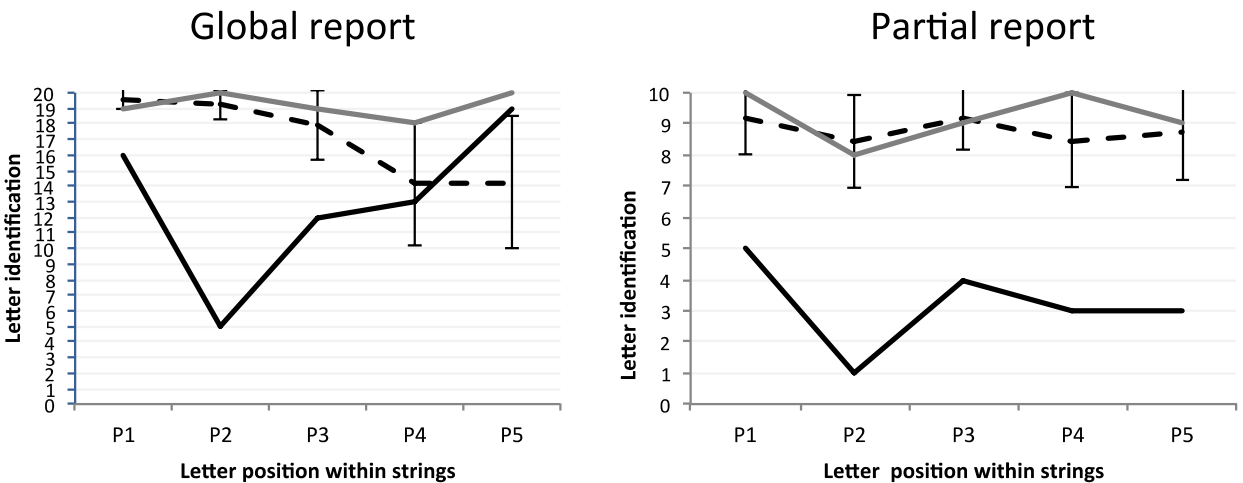
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20 Figure 2: (A) Procedure of global (a) and partial (b) report (Experiment 1); (B) Number or  
21 letters accurately identified in global and partial report as a function of letter position within  
22 strings for IG (black solid), ERB (grey solid) and the RA-matched control group (black  
23 hatch). For the controls, standard error bars are depicted for each position.

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### *Results:*

In global report (Figure 2B), IG reported 65 letters, which is significantly less ( $t_{\text{modified}(107)} = -2.24$ ;  $p = 0.014$ ) than ERB (96 letters) and the RA-matched controls (mean RA score = 85.11 (9.8);  $t_{\text{modified}(108)} = -2.04$ ,  $p < 0.05$ ). The ANOVA computed on the control data with letter position as an intra-subject factor showed a significant letter position effect ( $F(4; 428) = 156.33$ ;  $p < .001$ ), reflecting better performance on the leftmost than the rightmost letters. Most of the variance (90.25%) in controls was explained by a linear function. A cubic function accounted for a small additional part of variance (6.77%). IG's response pattern did not show the left-right gradient characteristic of the controls. She was poor at identifying the letters in position 1, 2 and 3 ( $t_{\text{modified}(108)}$ : P1 = -5.2; P2 = -14.8; P3 = -2.66; all  $p < 0.05$ ) but showed preserved performance on the rightmost letters (P4 and P5). Her performance pattern was deviant and well described by a cubic function that accounted for 97% of variance.

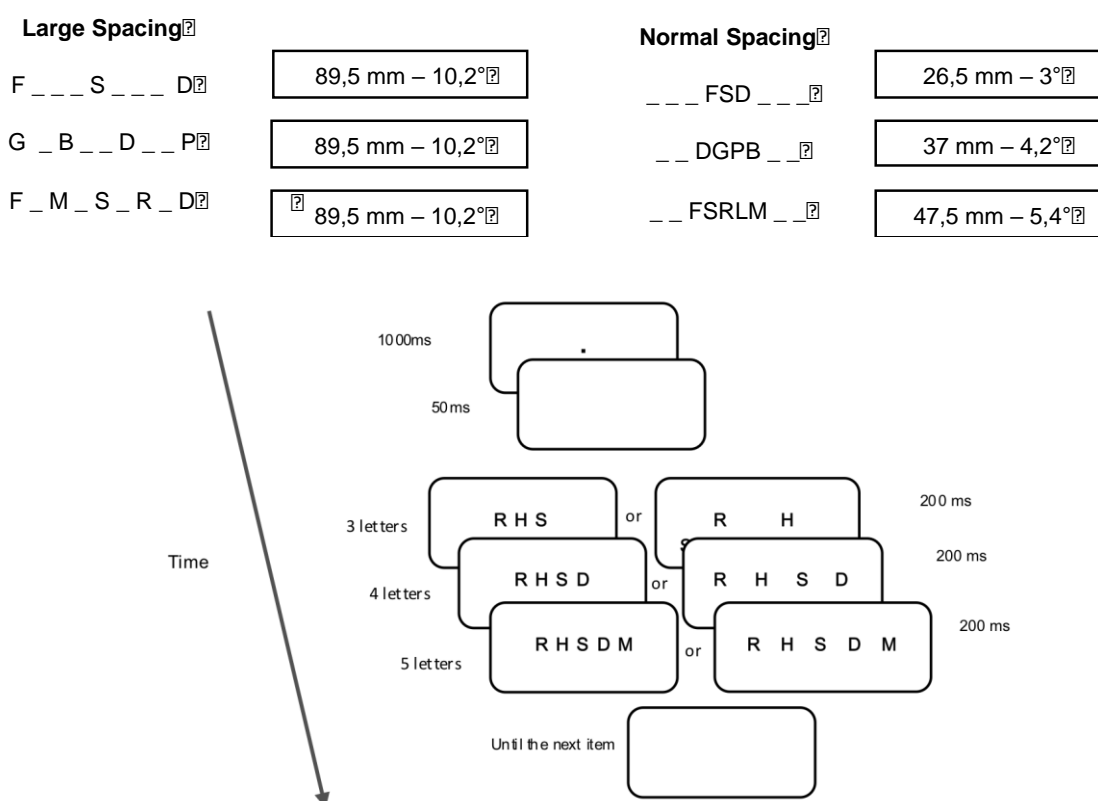
In Partial Report (Figure 2B), IG only reported 16 target letters (out of 50), a performance well below that of ERB (mean Partial Report score = 46;  $t_{\text{modified}(107)} = -4.93$ ;  $p < 10^{-6}$ ) and the controls (mean = 44.01 (4.3);  $t_{\text{modified}(108)} = -6.48$ ,  $p < 0.05$ ). Letter report was significantly impaired in IG whatever the position of the target in the string (all  $t_{\text{modified}} < -1.66$ ). In the controls, the response pattern was characterized by a main position effect ( $F(4, 404) = 5.66$ ;  $p < .0002$ ). Regression analyses showed that 68% of the variance of RA controls' pattern was accounted for by a linear function and an additional 31.33% by a quartic function. IG's performance pattern was very atypical and could not be accounted for by either a linear or a quartic function.

#### *3.1.2. Experiment 2: Effect of String Length and Interletter Spacing in Global Report*

*Participants:* The participants were IG, ERB and the same RA-matched control group as in Experiment 1.

*Stimuli:* Nineteen letter-strings made of 3, 4 or 5 letters were build up from 15 consonants (B, C, D, F, H, J, L, M, N, P, R, S, T, V). Each letter was around 7mm in height and 5.5 mm in width. A given letter was never used twice in the same string and each letter was used 24 times: 10 times in the 30 5-letter strings, 8 times in the 30 4-letter strings and 6 times in the 30 3-letter strings. Each letter was used twice in each position for each of the three lengths. The 30 strings of each length were presented in two conditions of normal and large inter-letter spacing (Figure 3A). In the normally spaced condition, the inter-letter spacing was of 5 mms (close to 1 character space) whatever string length, so that strings of 3, 4 and 5 letters subtended an angle of 3 degrees, 4.2 degrees and 5.4 degrees respectively (at a distance of 50 cm from the computer screen). In the large spacing condition, the whole letter-string subtended an angle of 10.23° (corresponding to 89.5 mm at a distance of 50 cm) whatever the string length so that the distance between adjacent letters varied from 36.5 mm (around 6 character spaces) for the 3-letter strings, to 22.5 mm (around 4 character spaces) and

1 15.5 mm (between 2 and 3 character spaces) for the 4 and 5-letter strings respectively.  
 2 Letters were presented in upper case (Genova 24) in black on a white background.  
 3 *Procedure:* Each trial began with a 1000 ms fixation point, displayed at the center of the  
 4 computer screen (Figure 3). This was followed by a blank screen for 50 ms, then the letter-  
 5 string was centrally displayed for 200 ms. The six conditions of length and spacing were  
 6 presented by blocks. After each trial, the participant was asked to orally report the name of  
 7 the letters he had identified. In each block, the participants carried out 10 training trials with  
 8 feedback. No feedback was provided during the experimental trials. The dependent  
 9 measure was the number of letters accurately identified (identity not location) out of a  
 10 maximal score of 75, 60 and 45 for the three length-by-spacing conditions.  
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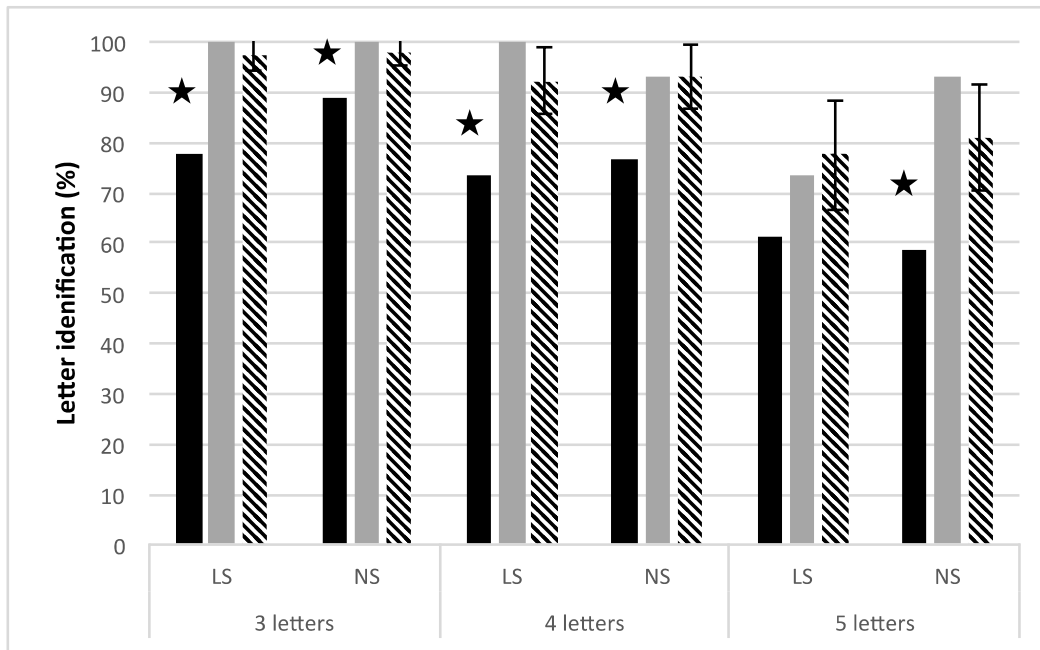
13 Figure 3: The spacing and length conditions of global report in Experiment 2

14

15 **Results**

16 An ANOVA with Length (3, 4 and 5 letters) and Spacing (normal and large) as within-subject  
 17 factors was carried out on the accuracy rate of the RA-matched controls. Results (see  
 18 Figure 4) showed a significant main effect of length ( $F(2, 214) = 407.77$  ;  $p < .001$ ) and  
 19 spacing ( $F(1, 107) = 40.63$ ,  $p < .001$ ). The Length by Spacing interaction was significant ( $F(2,$   
 20  $214) = 13,04$ ,  $p < .001$ ). Planned comparisons showed that a spacing effect was only found  
 21 for 5-letter strings, the only condition in which more letters were accurately reported in the  
 22 normal than in the large spacing condition (81.05% vs. 77.48%). Performance of the  
 23 controls on the shorter strings (3 and 4 letters) was not affected by spacing. As shown on

1 Figure 4, IG performed lower than ERB in all conditions of length and spacing (all  $t_s < -1.84$ ,  
 2 all  $p_s < .035$ ), except for the 5 letter condition of large spacing ( $t_{\text{modified}(107)} = -0.78$ ;  $p = .22$ ).  
 3 Comparison with the RA-matched group of control participants showed that IG was severely  
 4 impaired. Her performance was poorer than for the controls in all conditions of length and  
 5 spacing (all  $t_s < -2.1$ ;  $p < .02$ ), except again for the 5 letter condition of large spacing ( $t_{(108)} = -$   
 6  $1.478$ ;  $p = 0.07$ ). IG did not show any disadvantage in the normal spacing condition as  
 7 compared to the large spacing condition (normal spacing=74.74 vs. large spacing=70.81),  
 8 thus showing the absence of crowding effect.



9  
 10 Figure 4 : Number of letters accurately identified by IG (black), ERB (grey) and the controls  
 11 (hatch) in the two conditions of normal (NS) and large (LS) spacing for the 3-, 4- and 5-letter  
 12 strings. The standard error bars are provided for the control group.

13 **3.1.3. Experiment 3: Multi-letter Sequential Report**

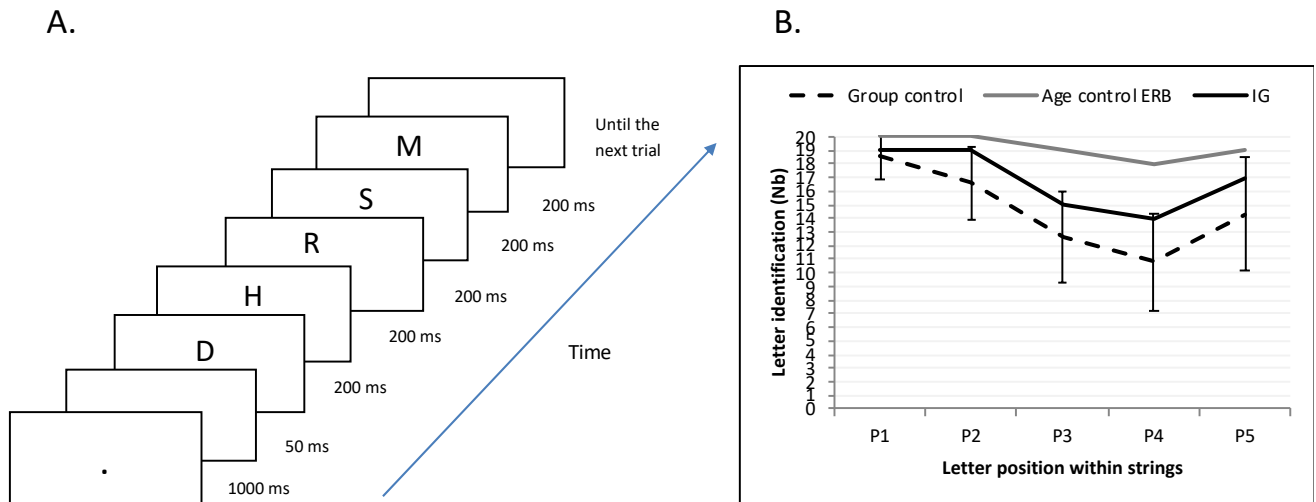
14 *Participants:* IG, ERB and a control group of 102 4<sup>th</sup> and 5<sup>th</sup> grade children were recruited as  
 15 controls. The control children had a mean chronological age of 11 years 4 months (mean  
 16 CA= 136.33 mths ; SD=8.6) and a similar reading age as IG (mean RA=120.02, SD=14.57;  
 17  $p > .05$ )

18 *Stimuli:* The strings of 5 consonants were constructed following the same constraints as in  
 19 Experiment 1.

20 *Procedure:* A central fixation point was presented for 1000 ms followed by a blank screen  
 21 for 50 ms (see Figure 5A). Then 5 letters were successively displayed one at a time at the  
 22 center of the computer screen. Each letter was displayed for 200 ms and was immediately  
 23 followed by the next letter (ISI = 0). Participants were asked to report as many letters as  
 24 possible, without any order or time constraints. They started naming letters at the end of the  
 25 sequential display. Ten training trials were proposed at the beginning of the task, for which  
 26 participants received feedback. No feedback was given during the 20 experimental trials.  
 27 The dependent measure was the number of letters accurately reported (identity not location)  
 28 across the 20 trials (maximal score = 100).

1 **Results:** The response patterns of IG, ERB and the controls in the sequential report task are  
 2 illustrated on Figure 5B. In the control group, performance was characterized by a main  
 3 position effect ( $F(4, 404) = 128,05, p < .001$ ), showing better report of the first than the last  
 4 letters. IG reported as many letters as the controls in this sequential report task (84 vs.  
 5 72.95,  $SD=10.32, t_{\text{modified}}=1.07; p=0.21$ ) and as many letters as ERB ( $t_{\text{modified}(102)}=-0.82;$   
 6  $p=0.21$ ). IG scores were within the normal range for all positions ( $t_{\text{modified}} > 0.22; \text{all } p > 0.05$ )  
 7 and her response pattern was characterized by a cubic function as for the controls.

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10 Figure 5: (A) The multi-letter sequential report procedure in Experiment 3; (B) Number of  
 11 letters accurately reported by IG (black line), ERB (grey line) and the controls (dotted line)  
 12 as a function of letter position within the sequential string. For the controls, standard error  
 13 bars are depicted for each position.

## 14 3.2. Temporal attention shifting

### 15 3.2.1. Experiment 4: Stream Segregation Threshold

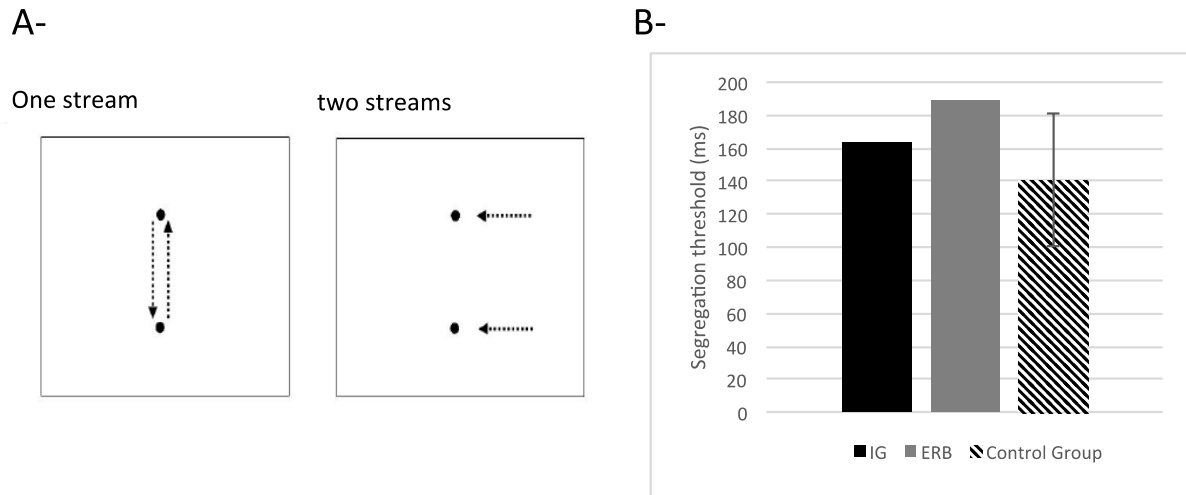
16 **Participants:** IG, ERB and a control group of 19 healthy young adults (mean CA= 19.4  
 17 years ;  $SD=0.6$ ) who participated in Lallier et al. (2010; Experiment 2).

18 **Stimuli:** Two black dots subtending  $0.1^\circ \times 0.1^\circ$  of visual angle were displayed in alternance  
 19  $2^\circ$  above and below a fixation cross along the vertical median line of the screen (see Figure  
 20 6A). The participants were asked to fixate the central cross so that the dots were foveally  
 21 presented, and could be perceived accurately without eye movements.

22 **Procedure:** The procedure was the same as in Lallier et al. (2010, Experiment 2). Within  
 23 each trial, a fixation cross, subtending  $0.5^\circ \times 0.5^\circ$  of visual angle appeared at the center of  
 24 the screen for 500 ms, followed by the two dots that alternated at different time intervals  
 25 (SOAs). After each trial, the participants reported whether they had perceived one stream or  
 26 two streams in a forced-choice paradigm. Each trial began with a 300 ms SOA, yielding a  
 27 systematic one-stream answer in all participants. The SOA was then decreased by steps of  
 28 40 ms, until the stimuli were perceived as two streams. The SOA was then increased or  
 29 decreased by steps of 20 ms until the next perception change. Steps of 10 ms and 5 ms  
 30 were then used to better estimate the segregation threshold that was defined as the mean



1 SOA over the last ten trials. Before the testing phase, a short training session was proposed  
 2 to the participants. During this practice period, an unambiguous one-stream stimulus  
 3 (SOA=400ms) and an unambiguous two-stream stimulus (SOA = 50 ms) were presented to  
 4 be associated with the appropriate schematic drawings (see figure 6A). After each trial,  
 5 participants answered by pointing at the drawing corresponding to the pattern they had  
 6 perceived. When unsure, they were instructed to guess.



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 8 Figure 6: (A) Schematic representation of the visual stream segregation procedure  
 9 (Experiment 3). The dotted arrows symbolise the one-stream (longer SOAs) or two stream  
 10 (shorter SOAs) conditions. (B) Segregation threshold for IG (black), ERB (grey) and the  
 11 controls (hatch) in milliseconds. The standard error bars are provided for the control group.

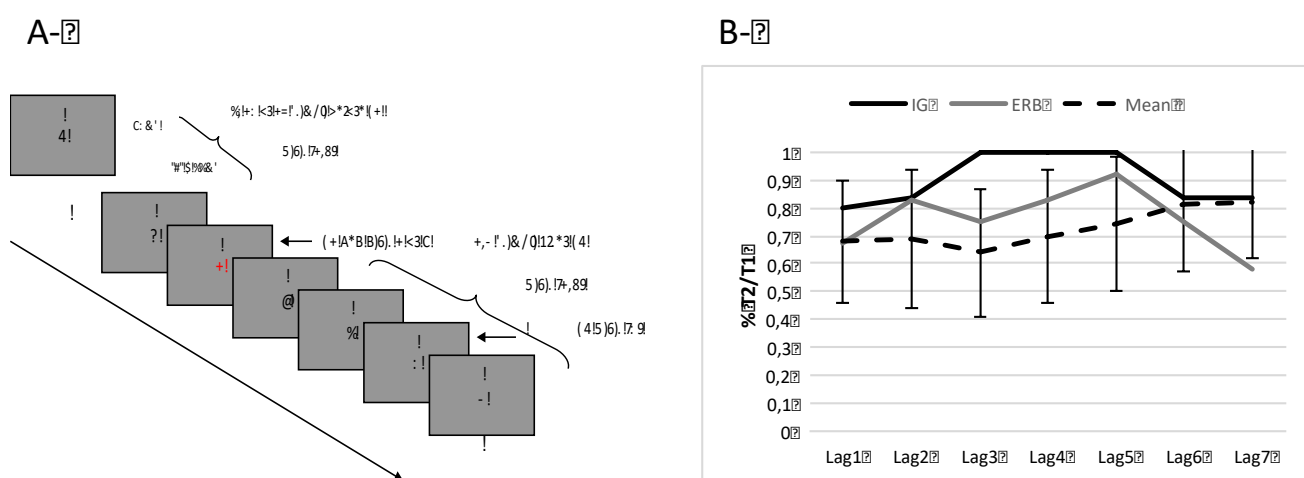
12  
 13 **Results:** The segregation thresholds (Figure 6B) were estimated at 141.1 ms (SD=40.4) in  
 14 the young adult healthy participants. The segregation thresholds of IG (threshold= 163.9  
 15 ms;  $t_{\text{modified}} = -0.59$ ) and ERB (threshold= 189.79 ms;  $t_{\text{modified}} = -0.51$ ) did not differ significantly  
 16 from those of the controls and they did not differ between ERB and IG ( $t_{\text{modified}(18)} = -0.45$ ;  
 17  $p = 0.33$ ).

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 19 **3.2.2. Experiment 5: Attentional Blink**

20  
 21 **Participants:** IG, ERB and a RA-matched control group of 18 children who were 10 year 3  
 22 month old on average (mean=123.72, SD= 6.14) and had a normal reading age (mean =  
 23 123.83, SD= 11.99).

24 **Stimuli:** The stimuli were black or red digits (from 0 to 9; Arial font) that subtended a visual  
 25 angle of  $0.7^\circ \times 0.7^\circ$  at a viewing distance of 60 cm. They appeared on a grey background  
 26 (red: 192; green: 192; Blue: 192). The digits were displayed at the center of the computer  
 27 screen in rapid serial presentation. Each digit was presented 40 ms and was followed by a  
 28 grey screen for 60 ms before the onset of the next digit, thus yielding a stimulus rate of 10  
 29 items/second. Each trial consisted of a sequence of 15, 19 or 23 digits which included a  
 30 single red digit that was either a 1 or a 5 (50% probability).

1 *Procedure:* The procedure from Lallier et al. (2010) is illustrated on Figure 7A. Two  
 2 conditions were proposed, a dual and a single conditions. In the dual condition of attentional  
 3 blink, the participants had to identify a first target (T1), then detect a second target (T2). The  
 4 red digit ("1" or "5") was the T1 target to be identified. T1 occurred in all the sequences but  
 5 could appear with the same probability in the 7<sup>th</sup>, 11<sup>th</sup> or 15<sup>th</sup> position. The black digit "0" was  
 6 the T2 target to be detected. T2 was presented at varying time intervals following T1, from  
 7 lag 1 (SOA =100ms, T2 immediately follows T1) to lag 7 (SOA = 700ms, 6 intervening  
 8 digits). T2 was present in half of the trials. In the single condition, there was no T1 targets  
 9 and the participants only had to detect the black digit "0" when present. The single condition  
 10 was designed to ensure that participants could accurately process a single target (T2) when  
 11 presented in a stream of rapidly presented stimuli. Variations in the drop of performance  
 12 according to T2 temporal position was taken as an index of the attentional blink. Each  
 13 participant completed two successive blocks of 84 trials, the single task block first, then the  
 14 dual task block. A practice of 15 trials was proposed before the single task condition. The  
 15 experiment was administered in a dimly lit room, using E-Prime software on a PC computer  
 16 (computer screen=17-in.; refresh rate=85Hz). Each trial was initiated by a fixation cross,  
 17 presented for 500ms at the centre of the screen. The sequence of stimuli began 100 ms  
 18 after the fixation cross offset. After each trial, the participant had to report orally whether T2  
 19 was present or not for the single condition and to name the red digit ("1" or "5") and report  
 20 whether T2 was present or not in the dual condition. The experimenter initiated the next trial  
 21 by pressing the space bar on the keyboard. No feedback was given during the experimental  
 22 trials.



23  
 24 Figure 7: (A) illustration of the Attentional Blink protocole (Experiment 4); (B) Performance  
 25 of IG (black line), the control group (dotted line) and ERB (grey line) in the dual condition.  
 26 For the controls, standard error bars are depicted for each lag.

27 *Results:* Target detection accuracy was high in the single condition for IG ( $M_{IG}=100\%$ ), ERB  
 28 ( $M=86,9\%$ ) and the control participants ( $M =84\%$ ,  $SD=14,33$ ) with no significant difference  
 29 between IG and ERB ( $t_{modified(17)}=0.65$ ;  $p=0.26$ ). IG performed at ceiling and her performance  
 30 did not differ from that of the controls at any lag (all  $t_{s_{modified}} >.05$ ), showing very good ability  
 31 to identify a target within rapid serial presentation. For the AB assessment in the control  
 32 group, an analysis of Variance (ANOVA) with condition (single, dual) and lag (1, 2, 3, 4, 5,  
 33 6, 7) as within-subjects factors was carried out on T2 detection rate when T1 was correctly

1 identified. The results are provided on Figure 7B. The controls demonstrated a trend for a  
2 Condition by Lag interaction ( $F(6; 102) = 2.036, p = .067$ ), suggesting an attentional blink.  
3 Planned comparisons (with Bonferroni correction) showed that they were less prone to  
4 identify the target in the dual than in the single condition at lag 1 ( $F(1, 17) = 10.65;$   
5  $p=0.005$ ), lag 3 ( $F(1,17)= 8.83; p=0.0085$ ) and lag 4 ( $F(1,17) = 11.13; p=0.0039$ ). The  
6 controls showed a lag-2 sparing. Overall, the performance of the controls was characterized  
7 by an attentional blink during a time window of 100-400 ms after T1 presentation. The  
8 performance of IG (Figure 7B) did not differ significantly from that of the controls in any T2  
9 temporal position (all  $t_{\text{modified}}$  non-significant). In the same way, ERB performed as the  
10 controls (all modified t-tests non-significant).

11 To investigate the duration of the AB exhibited by IG, her dual condition performance was  
12 compared to the single condition performance of ERB and the controls at each lag. IG  
13 showed a performance similar as the controls and ERB performance (all  $p>.05$ ), which was  
14 also found for ERB. Lastly, in order to determine any AB depth deficit in IG, we computed  
15 the difference between the single and dual condition on T2 detection at each lag for each  
16 control participant, for ERB and for IG. The attentional blink depth was similar in IG, ERB  
17 and the controls at any lag (all modified t-tests non-significant).

18

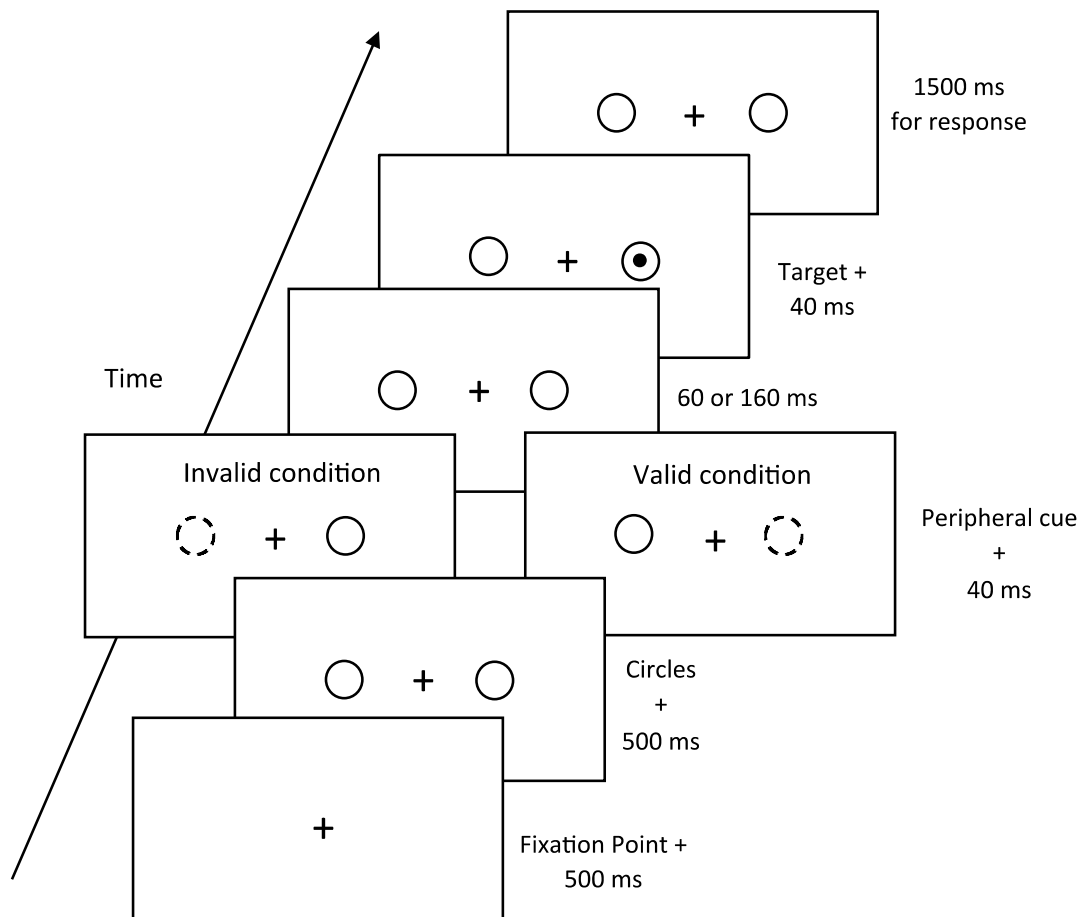
### 19 3.3. Spatial Attention Shifting

#### 20 3.3.1. *Experiment 6 : Exogenous Orientation of Spatial Attention*

21 *Participants:* Twenty-six children participated as controls. They were 10 year 10 month old  
22 on average (Mean= 130.11, SD = 3.65) for a reading age of 12 years on average (mean=  
23 144.46; SD = 16.61).

24 *Procedure:* As shown on Figure 8, each trial started with a fixation cross displayed at the  
25 centre of the computer screen for 500 ms. Two circles ( $2.5^\circ$  diameter) were then  
26 simultaneously displayed for 500 ms at  $8^\circ$  of eccentricity from the fixation point in the left  
27 and right visual fields. The rapid offset/onset (40 ms) of one of the two circles was used as a  
28 peripheral cue to attract attention randomly to the left or right circle. The target to be  
29 detected was presented after two possible inter-stimulus intervals: ISI=60ms (SOA=100ms)  
30 or ISI=160ms (SOA=200ms). The target was a dot ( $0.5^\circ$ ) displayed for 40 ms at the center  
31 of one of the two circles. The peripheral cue was either valid (corresponding to the location  
32 of the following target; 50% of the trials) or invalid. Stimuli were white on a black  
33 background and had a luminance of  $24\text{cd/m}^2$ . Catch trials in which no target was presented  
34 were intermingled with the response trials.

35 The participants were seated 50cm from the monitor with their head in a chin rest. They  
36 were asked to respond as fast as possible to the occurrence of the target by pressing the  
37 spacebar on the keyboard with their right hand. The maximum time allowed for response  
38 was 1500ms. The task began with 6 training trials. The experimental session consisted of  
39 80 trials: 64 experimental trials (50%Valid, 50%Invalid), 16 catch trials (8 left and 8 right,  
40 50% 100ms, 50% 200ms SOA).

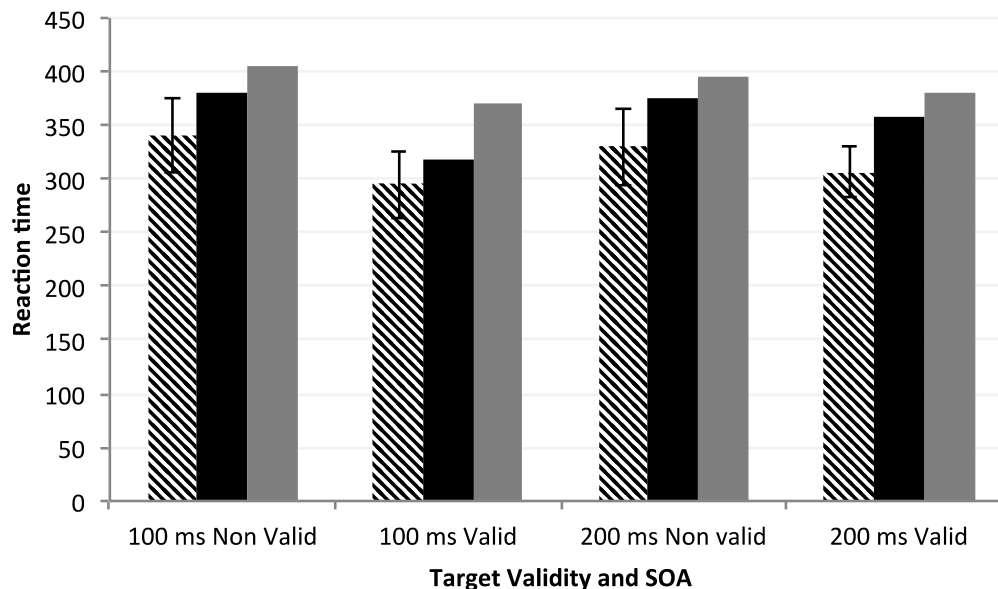


1

2 Figure 8: Procedure of the exogenous spatial attention task (Experiment 5).

3 *Results:* RTs for ERB, IG and the controls depending on the SOA and Cue Condition are  
 4 provided on Figure 9. A multifactorial ANOVA was performed on the control group RTs with  
 5 SOA (100ms vs. 200ms) and Cue Condition (valid vs. invalid) as within-subjects factors.  
 6 There was a significant main effect of Cue Condition ( $F(1, 25) = 65,033$  ;  $p < .05$ ), showing  
 7 that targets were detected faster when presented after a valid cue (mean  $RT_{valid} = 300.41$   
 8 ms,  $SD_{valid} = 28,77$  vs. mean  $RT_{invalid} = 335.34$  ms,  $SD_{invalid} = 36,05$ ). The SOA by Cue  
 9 Condition interaction was significant ( $F(1, 25) = 19,40$  ;  $p < .002$ ). The validity effect was  
 10 larger for a 100ms SOA than for a 200ms SOA (validity effect<sub>100</sub> = -46.65 ms,  $SD = 22.85$   
 11 vs. validity effect<sub>200</sub> = -23.19 ms,  $SD = 27.75$ ), suggesting an automatic engagement of  
 12 exogenous attention followed by a progressive disengagement. There was no significant  
 13 main effect of SOA ( $F < 1$ ).

14 IG and ERB exhibited similar validity effects at both the 100ms SOA (controls' mean = -  
 15 46.65 ms,  $SD = 22.85$  ms; validity effect in IG= -61.625 ms vs. ERB= -35.125 ms,  $p > 0.05$   
 16 with  $t_{modified(25)} = 0.21$ ) and the 200ms SOA (control mean = -23,19,  $SD = 27.75$  ms; validity  
 17 effect in IG= -15.5 ms vs. ERB = -13.25ms,  $p > 0.05$  with  $t_{modified(25)} = -0.06$ ). As for the  
 18 controls, the validity effect of patient IG decreased with increasing SOA, indicating normal  
 19 engagement of exogenous attention (better at 100 ms than 200 ms) after bilateral SPL  
 20 damage. The index of temporal decrease (validity effect at 100 ms SOA minus validity effect  
 21 at 200 ms SOA) was computed for each participant. This index did not differ between IG  
 22 and ERB ((IG = -46.13 ms; Controls = -23.46 ms,  $SD_{control} = 26.63$  ms; ERB = -21.88 ms,  
 23  $p > 0.05$  with  $t_{modified(25)} = -0.64$ ).

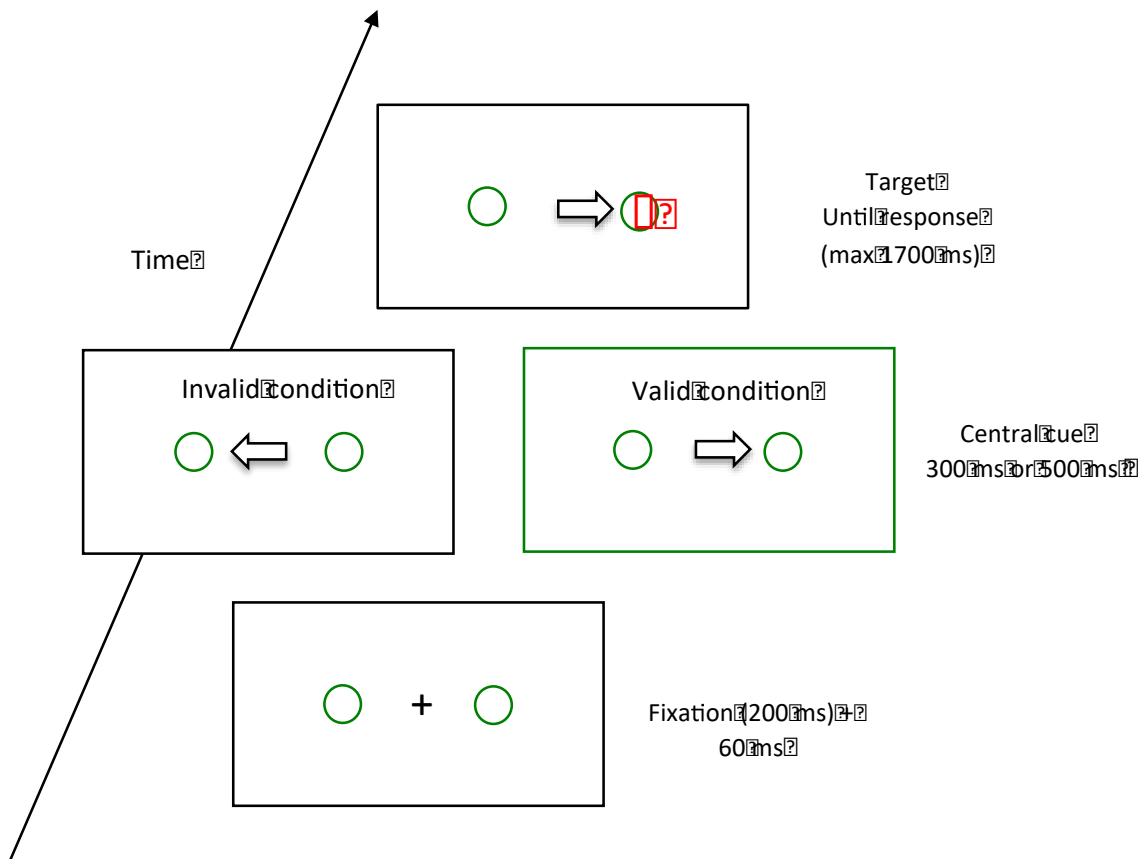


1  
 2 Figure 9: Mean reaction times in target detection for the two exogenous conditions of cueing  
 3 (valid or invalid) and SOA (100 ms or 200 ms) for the control group (hatch), IG (black) and  
 4 ERB (grey). Standard error bars are depicted for the control group.

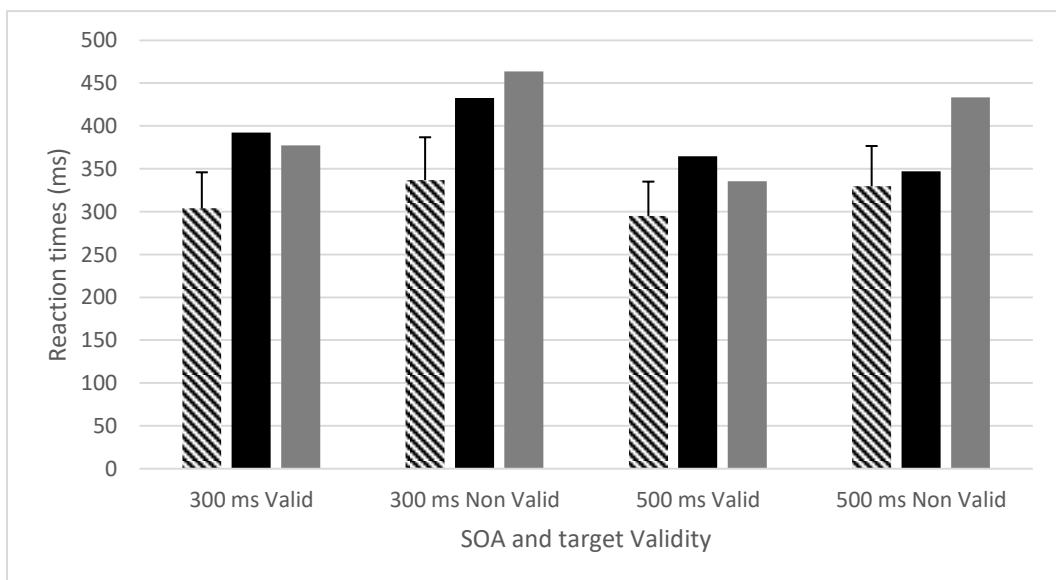
5  
 6 **3.3.2. Experiment 6 : Endogenous orientation of spatial attention**  
 7 *Participants:* IG, ERB and a control group of 71 healthy young adults (mean age = 19.8  
 8 years) whose performance on the voluntary orienting task was taken from a previous study  
 9 (Striemer et al. 2007) participated in Experiment 6.

10 *Stimuli and procedure:* A 80% predictive central arrow cue was used for voluntary orienting.  
 11 Some targets were presented without cues to examine response times for simple target  
 12 detection. Target location was indicated by green circles subtending 2° of visual angle,  
 13 presented 12° left and right of fixation (see Figure 10). The target was a red circle presented  
 14 within one of the green circles. The coloured stimuli were presented on a white background.  
 15 After a stimulus onset asynchrony (i.e. time between cue and target onset; SOA) of 300 or  
 16 500 ms, targets appeared at the cued (valid) or uncued (invalid) location. The participants  
 17 responded by pressing a button with the right hand on the keyboard. They were seated  
 18 50cm from the monitor with their head in a chin rest. For patient IG and her control ERB, a  
 19 longer SOA (800 ms) was additionally tested.

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 22  
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1  
2 Figure 10: Procedure of the endogenous condition of visual attention orientation.  
3  
4 Results : Reaction times for target detection in the endogenous condition are provided on  
5 Figure 11 for IG, ERB and the control group.

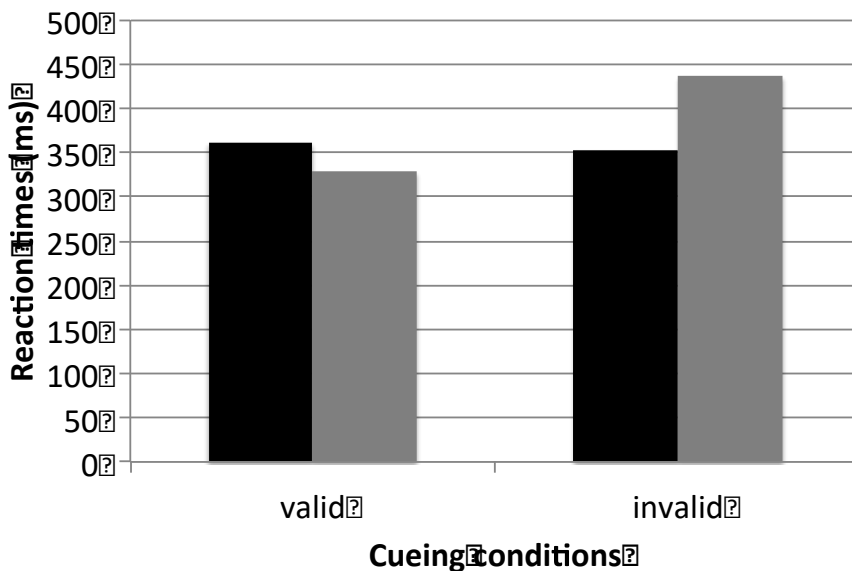


6  
7 Figure 11: Mean reaction times for target detection in the endogenous condition of spatial  
8 orientation (Experiment 6) depending on cue condition (valid or invalid) and SOA (300 ms or  
9 500 ms) for IG (black), the control group (hatch), and ERB (grey).

1 The ANOVA performed on the control RTs showed main effects of SOA and cue condition  
2 ( $F > 12$ ,  $p < 0.05$ ). RTs were faster in the long compared to the slow SOA and in the valid  
3 compared to the invalid cueing condition. There was no significant SOA by Validity  
4 interaction ( $F(1,70) = 0.4$ ;  $p > 0.05$ ), showing that, contrary to the exogenous condition, the  
5 validity effect was constant in time in the context of endogenous attention.

6 Contrary to the control group and ERB, IG was slower at detecting the target in the valid  
7 than the invalid condition at the 500ms SOA, which suggests an inhibition of return.  
8 Actually, IG and ERB exhibited different validity effects at both 300ms SOA (controls' mean  
9 = -32.88 ms,  $SD = 18.00$ ; validity effect in IG = -40.64 ms vs. ERB = -86.0 ms,  $p < 0.05$  with  
10  $t_{\text{modified}(70)} = 1.78$ ) and 500ms SOA (control mean = -34.57 ms,  $SD = 17.67$ ; validity effect in  
11 IG = 17.30 ms vs. ERB = -98 ms;  $p < 0.05$  with  $t_{\text{modified}(70)} = 4.6$ ,  $p < 0.05$ ). The index of temporal  
12 decrease (validity effect at 300 ms SOA minus validity effect at 500 ms SOA) was computed  
13 for each participant. IG exhibited a pathological decrease of the validity effect between 300  
14 ms --where invalidly cued targets were detected slower than validly cued targets-- and 500  
15 ms --where she showed an inhibition of return suggesting that she could not maintain her  
16 attention voluntarily as long as the controls and ERB ( $M_{\text{controls}} = 1.54$ ;  $SD_{\text{controls}} = 20.66$ ;  $IG_{\text{index}}$   
17 of decrease = -58.3;  $ERB_{\text{index of decrease}} = 12.0$ ,  $p < 0.05$  with  $t_{\text{modified}(70)} = -2.41$ ).

18 This temporal aspect of endogenous attention deficit was confirmed by an additional testing  
19 of patient IG --and comparison with ERB-- at a longer (800ms) SOA. Results are presented  
20 on Figure 11. Contrary to ERB, IG did not benefit from the 80% valid cues. She did not  
21 show faster reaction times for the valid than the invalid condition (IG validity effect = 8.5 ms)  
22 while ERB exhibited a large validity effect (ERB validity effect = -108 ms).



23  
24 Figure 12: Reaction times of IG (black) and ERB (grey) in the valid and invalid cueing conditions of  
25 endogenous attention (Experiment 6) for an SOA of 800ms.

26

#### 27 4. Discussion

1 IG, a bilateral SPL damaged patient, performed a series of visual attention tasks that  
2 assessed the different facets of visual attention for which dyslexic participants have been  
3 shown to exhibit a deficit. Our main goal was to provide new insights on the facets of visual  
4 attention that specifically relate to the superior parietal lobules. We reasoned that evidence  
5 for deficits on the whole set of tasks in IG would support the existence of a single attentional  
6 system related to a single neural network that includes the SPLs. As a direct consequence,  
7 such a unitary account would predict that children with developmental dyslexia would show  
8 simultaneous deficits on all types of tasks and that the visual attention deficits reported in  
9 the dyslexic population do reflect a single visual attention dysfunction, as sometimes  
10 suggested (Facoetti et al., 2006; Vidyasagar & Pammer, 2010). On the contrary, evidence  
11 for a dissociation between two subsets of preserved vs. impaired VA tasks in IG would  
12 clarify the type of visual attention skills that specifically relate to the SPLs. Such dissociation  
13 would support the existence of at least two attentional systems that relate to distinct neural  
14 substrates. As a consequence, dyslexic children might show selective impairment of one or  
15 the other attentional network. We could further expect these selective impairments to be  
16 associated with distinct cognitive deficits in developmental dyslexia.

17 IG was first administered tasks of VA span (Experiment 1 and 2). In *Experiment 1*, she was  
18 presented with briefly displayed 5-consonant strings in conditions of global and partial  
19 report. In both conditions, her performance was far poorer than that of the controls, showing  
20 that she could only identify a few consonants when simultaneously presented within 5-  
21 consonant strings. To better grasp the severity of her disorder, sequences of 3, 4 and 5  
22 consonants were administered in *Experiment 2* but in the global report condition only.  
23 Results showed that her very poor performance extended to shorter strings of 3 and 4  
24 consonants. Her poor performance on these two tasks of simultaneous multi-letter  
25 processing (*Experiment 1 and 2*) contrasted with her very good report performance on  
26 similar strings of five letters when presented sequentially in *Experiment 3*. IG performed at  
27 the level of ERB and the controls on this later task and showed a similar response pattern.  
28 She was quite good at processing letters when briefly presented one at a time, thus  
29 showing that her poor performance on the VA span tasks (*Experiment 1*) can not be  
30 attributed to poor oral report skills, poor single letter processing or poor verbal short-term  
31 memory. A similar dissociation --poor multi-letter simultaneous processing but good multi-  
32 letter sequential processing—was previously reported in VA-span-impaired dyslexic children  
33 (Lassus-Sangosse et al., 2008; Valdois et al., 2011).



1 IG's poor performance on the VA span tasks is well in line with previous evidence for a  
2 SPLs dysfunction in children with VA span dyslexia (Lobier et al., 2014; Peyrin et al., 2011,  
3 2012; Reilhac et al., 2013). Like IG, dyslexic children with SPL bilateral dysfunction show  
4 poor performance in global and partial report tasks despite fast and normal single letter  
5 processing. In line with previous neuroimaging data in healthy (Lobier et al., 2012) and  
6 dyslexic (Lobier et al., 2014) individuals, the current findings confirm that the SPLs are  
7 involved in multi-element (here letters, but true for non-alphanumeric characters as well,  
8 Lobier et al., 2012, 2014) visual processing but not in the processing of the same elements  
9 when presented in isolation.

10 Although our previous studies on developmental dyslexia mainly used sequences of 5 (or  
11 6) items, other studies reported poor processing for shorter 4-digit strings in dyslexic  
12 children (Hawelka & Wimmer, 2005). The present findings show that a damage of the SPLs  
13 yields poor performance for even shorter letter strings. They suggest that future studies  
14 should explore VA span skills in dyslexic children more in depth, through systematic  
15 variations of string length.

16 Experiment 2 further assessed whether performance was sensitive to lateral interference  
17 between adjacent letters, or crowding (Gori & Facoetti, 2015; Martelli et al., 2009; Whitney &  
18 Levy, 2010). The classic global and partial report tasks have been initially designed to  
19 minimize potential crowding effects by systematically increasing interletter spacing. To  
20 ensure that poor performance on VA span tasks in *Experiment 1* was not just the  
21 consequence of very severe crowding, spacing between letters was drastically increased in  
22 the large spacing condition of Experiment 2. IG showed poor performance irrespective of  
23 spacing for the 3 and 4 letter strings. A spacing effect was observed for 5-letter strings but  
24 showed an advantage for the small spacing condition, against any crowding interpretation.  
25 The overall findings suggest that IG's poor performance on VA span tasks is free from  
26 lateral interference and primarily reflects a difficulty to process multiple letters within strings.  
27 Another important consequence of the current findings is that bilateral SPL damage did not  
28 yield larger crowding effect, thus suggesting that the SPLs are not involved in crowding.

29 In Experiment 4 and 5, IG was administered tasks of stream segregation and attention blink  
30 to assess her temporal attention shifting skills. In *Experiment 4*, stream segregation  
31 threshold – corresponding to the inter-stimulus interval for which the participants could not  
32 decide whether they perceived one or two visual streams – was estimated. The segregation  
33 threshold was found similar in IG and the controls, showing that she had no difficulty to  
34 quickly engage her visual attention on a stimulus and disengage it automatically to process

1 the following one. Her preserved temporal attentional shifting skills were confirmed in  
2 *Experiment 5*, in which IG showed similar attentional blink duration and similar attention  
3 blink depth as the controls. Overall, these findings demonstrate preserved temporal  
4 attention shifting in IG despite a severe VA span deficit. A dissociation between VA span  
5 and temporal attention shifting was previously reported in a case study of developmental  
6 dyslexia (Lallier et al., 2010c). Evidence for the absence of correlation between visual  
7 stream segregation threshold and VA span in children with developmental dyslexia further  
8 supports the independence of the two underlying attentional systems (Lallier et al., 2009;  
9 see also Lallier & Valdois, 2012).

10 Spatial attention shifting skills were explored in the two last experiments. In the exogenous  
11 cueing condition of spatial attention (*Experiment 6*), IG showed a validity effect of the same  
12 amplitude as the controls. She detected the target faster when the peripheral cue attracted  
13 her attention toward the target location (valid condition), showing that she was quite efficient  
14 at engaging attention on the right or left visual field following exogenous cueing. In contrast,  
15 her performance was rather atypical in the endogenous condition of spatial attention  
16 (*Experiment 7*). In this experiment where a central arrow pointing left or right indicated the  
17 location of the upcoming target with 80% predictive power, the controls showed faster  
18 responses and a stronger validity effect at longer SOAs. A validity effect was only found at  
19 the shorter (300 ms) SOA in IG but not for longer SOAs (500 and 800 ms), suggesting that  
20 she was unable to maintain her attention voluntarily as long as the controls. Many studies  
21 have reported a deficit in exogenous cueing in developmental dyslexia (Facoetti et al., 2005,  
22 2010b; Roach & Hogben, 2004; Ruffino et al., 2014) or at risk pre-readers (Facoetti et al.,  
23 2010a; Franceschini et al., 2012) but the results were less consistent with respect to  
24 endogenous cueing in the few studies that assessed the two cueing conditions in the same  
25 participants (Facoetti et al., 2000, 2006). Reversely, a deficit specific to the endogenous  
26 cueing condition was emphasized in Chinese dyslexic children in the absence of exogenous  
27 spatial attention deficit (Liu, Liu, Pan & Xu, 2018). An additional key point here is strong  
28 evidence in support of distinct anamo-functional attentional systems supporting endogenous  
29 (goal-driven) vs. exogenous (stimulus-driven) spatial attention (Chica et al., 2013).

30 Overall, the present study provides strong evidence for the existence of distinct attentional  
31 systems that rely on distinct neural substrates. The exploration of IG visual attention skills  
32 clearly shows that bilateral superior parietal lobule damage does not result in a severe and  
33 general visual attention deficit but rather affects some specific dimensions of visual  
34 attention. IG shows impaired performance in VA span tasks of multi-element simultaneous

1 processing and in the endogenous condition of spatial attention shifting but preserved skills  
2 in tasks of temporal attention shifting and exogenous spatial cueing. These findings strongly  
3 support the existence of distinct attentional systems, one of which involves the SPLs,  
4 themselves part of the dorsal attentional network-DAN (Chica et al., 2013; Corbetta &  
5 Shulman, 2002). They help clarifying the pattern of results reported in the scientific literature  
6 on developmental dyslexia. Deficits of VA span and temporal and spatial attention shifting  
7 have consistently been reported in individuals with DD but no study explored all three facets  
8 of visual attention in the same participants, so that the question remains whether this  
9 constellation of attentional deficits is systematically associated (or not) in the dyslexic  
10 population. The current findings clearly suggest that selective deficits of VA span and  
11 endogenous spatial cueing should characterize a first subset of dyslexic children who shows  
12 a bilateral SPL dysfunction while at least a second subset might show selective deficit of  
13 temporal attention shifting and exogenous spatial attention.

14 Such a dichotomy is consistent with the hypothesis put forward by Lallier & Valdois (2012)  
15 regarding the independence of the VA span theory (Bosse & Valdois, 2007) and the  
16 sluggish attentional shifting (SAS, Hari & Renvall, 2001) theory of developmental dyslexia,  
17 two theoretical accounts that further dissociate with respect to the contribution of visual  
18 attention difficulties to phonological deficits. On one hand, a large body of research shows  
19 that VA span and phoneme awareness deficits typically dissociate in developmental  
20 dyslexia (Bosse et al., 2007 ; Germano et al., 2014 ; Lallier et al., 2010c ; Zoubrinetzky et  
21 al., 2014 ; See Saksida et al., 2016 for contradictory results and Reilhac et al., submitted,  
22 for a response) and that VA span and phoneme awareness are independent unique  
23 predictors of reading performance in typical readers (Bosse & Valdois, 2009 ; Lobier et al.,  
24 2013 ; Valdois et al., submitted ; van den Boer et al., 2013). On the other hand, sluggish  
25 temporal attentional shifting typically cooccurs with phonological deficits in individuals with  
26 developmental dyslexia (Lallier et al., 2009, 2010a, 2010b, 2010c) and exogenous spatial  
27 attention deficits were reported in only a subgroup of dyslexic children with very poor  
28 pseudo-word reading and poor phonological skills (Facoetti et al., 2010; Ruffino et al., 2014;  
29 see however, Banfi, Kemény, Gangl, Schulte-Körne, Moll & Manderl, 2017). We would thus  
30 expect the first subset of dyslexic children with SPLs dysfunction to show poor VA span,  
31 atypical spatial endogenous attention but preserved phonological skills while dyslexic  
32 children with poor temporal attention shifting and poor exogenous spatial attention would be  
33 further impaired in phonological processing. Some recent findings further suggest that the  
34 latter but not the former would show a categorical perception deficit (Zoubrinetzky et al.,  
35 2016).

1 The current findings also provide new insights on potential association/dissociation with an  
2 asymmetric distribution of attention between the left and right hemifields --or minineglect--  
3 and atypical performance in visual search tasks depending on dyslexia subtypes.  
4 Interhemispheric asymmetries have been searched for in developmental dyslexia and  
5 sometimes reported (Facoetti & Molteni, 2001; Facoetti & Turatto, 2000; Hari, Renvall &  
6 Tanskanen, 2001; Sireteanu et al., 2005). However, some case studies of dyslexic children  
7 with a VA span deficit failed to report any asymmetry between the left and right visual  
8 hemifields (Dubois et al., 2010; Valdois et al., 2011). IG's results are quite in line with these  
9 later reports, showing that a bilateral SPL damage does not yield visuo-spatial neglect.  
10 These findings are in line with the current literature on the neural substrates of spatial  
11 attention and unilateral spatial neglect. Lesions of the ventral attentional network-VAN --in  
12 particular the right temporo-parietal junction-- and not of the dorsal attentional network-DAN,  
13 are traditionally associated with unilateral spatial neglect (Chica et al., 2013; Mort et al.  
14 2003; Vallar & Perani, 1987). Moreover, although the VAN and DAN are known to interact,  
15 this interaction is not symmetrical. Recent neuroimaging results suggest that a structural  
16 lesion of the VAN affects the functioning of the DAN (Corbetta et al. 2005) while conversely  
17 a lesion of the DAN produces restricted deficits of spatial attention (Gillebert et al. 2011,  
18 Shomstein et al. 2010) with features of Balint syndrome (e.g. visual disorientation, deficits of  
19 global perception, shape identification in a cluttered field, see Pisella et al., 2015, 2013),  
20 resembling more to VA span dyslexia than the clinical picture of spatial deficits in neglect.  
21 The current findings are further in line with evidence that the right-hemispheric regions of  
22 the VAN are specifically involved in exogenous covert shifting of spatial attention, towards  
23 both the left and right visual hemifields whereas the DAN is involved in the spatial selection  
24 of objects for voluntary shifting of overt and covert attentional exploration (Chica et al.,  
25 2011; Corbetta et al., 2000; Corbetta & Shulman, 2011; Hopfinger et al., 2000; Kastner et  
26 al., 1999).

27 IG's lesion matches the parietal regions of the DAN. She has been previously studied in  
28 visual search and shows a reduced visuo-attentional window specifically when she faces  
29 stimuli made by a combination of lines (Khan et al., 2016). This deficit in visual search after  
30 bilateral SPL damage is in line with the impaired search performance specific to  
31 « multifeatures shapes » combining separable features previously reported in poor readers  
32 (Casco & Prunetti, 1986) and with evidence for a visual search deficit in VA span impaired  
33 dyslexic children (Lallier et al., 2013).

## 34 **5. Conclusion**

1 Exploration of distinct facets of visual attention in patient IG, who suffers a bilateral SPL  
2 lesion, supports the existence of distinct attentional systems that relate to distinct neural  
3 substrates. IG shows a lesion of the DAN yielding to poor multielement simultaneous  
4 processing (i.e. poor VA span) and poor endogenous spatial attention while temporal  
5 attention shifting and exogenous spatial attention are intact, showing that they relate to a  
6 distinct attentional network, quite probably the VAN. Exploration of patient IG further  
7 provides new insights on developmental dyslexia. A bilateral SPL dysfunction has been  
8 reported in a subset of dyslexic children who show poor VA span but preserved  
9 phonological skills. In line with the current findings, these dyslexic individuals are free from  
10 sluggish temporal attention shifting but impaired in visual search. They should further show  
11 impaired endogenous but preserved exogenous spatial attention, which remains to be  
12 systematically investigated. In contrast, the current findings suggest that the exogenous  
13 spatial attention and temporal attention shifting deficits reported in developmental dyslexia,  
14 actually defines another subset of dyslexic individuals who show associated phonological  
15 deficits but preserved VA span and might be more prone to show a left-right hemifield  
16 asymmetry in tasks of spatial processing. While the temporal and spatial attentional functions  
17 of the VAN and the DAN are both involved in the development of reading, we argue that  
18 they should nevertheless be distinguished. Evidence from IG allows making new predictions  
19 about developmental dyslexia, which will help clarifying the role of each attentional  
20 subsystem on reading acquisition and the consequences of a selective deficit of one or the  
21 other attentional system in developmental dyslexia.

22

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