Research report

A case study of developmental phonological dyslexia: Is the attentional deficit in the perception of rapid stimuli sequences amodal?

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\textbf{Abstract}

The attentional blink (AB) refers to a decrease in accuracy that occurs when participants are required to detect the second of two rapidly sequential targets displayed randomly in a stream of distracters. Dyslexic individuals have been shown to exhibit a prolonged AB in the visual modality, interpreted as evidence of sluggish attentional shifting (SAS). However, the amodal SAS theory predicts that the disorder should further extend to the auditory modality, then resulting in a phonological disorder as typically found in developmental dyslexia. Otherwise, it has been demonstrated that a visual attention (VA) span deficit contributes to the poor reading outcome of dyslexic individuals, independently of their phonological skills. The present study assesses the amodality assumption of the SAS theory together with questioning its relation with the VA span deficit. For this purpose, visual and auditory ABs were explored in a well compensated young adult, LL, who exhibits a pure phonological dyslexia characterised by poor pseudo-word processing and poor phonological skills but preserved VA span. The investigation revealed two different kinds of deficits in LL. Her AB was prolonged and marginally deeper in the visual modality whereas a primarily deeper in amplitude and a subtle prolonged AB was found in the auditory modality. The atypical performance patterns of LL in both modalities suggest that her perceptual attention disorder is amodal as predicted by the SAS theory. This amodal disorder was here reported in a dyslexic participant with a phonological disorder, well in accordance with the hypothesis that sluggish auditory attention shifting contributes to difficulties in phoneme awareness and literacy acquisition. Furthermore, prolonged VA blink was observed in the absence of VA span disorder, thus suggesting that visual attentional shifting and VA span might be distinct mechanisms, contributing independently to reading acquisition and developmental dyslexia.

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Developmental dyslexia is a specific disorder of learning to read, despite normal intelligence and adequate literacy instruction. The phonological deficit hypothesis (Frith, 1997; Snowling, 2000; Vellutino et al., 2004) assumes that an underlying phonological impairment is the core deficit in developmental dyslexia. Dyslexic individuals have been shown to exhibit phonological processing difficulties when engaged in tasks of phoneme awareness, phonological learning or non-word repetition (Gathercole and Baddeley, 1990; Pennington et al., 1990; Brady and Shankweiler, 1991; Frith, 1995; Mody et al., 1997). However, they further suffer from various sensory deficits which are not directly related to reading skills but might be responsible for their phonological impairment. In particular, a temporal processing deficit has been proposed as a more basic problem yielding to the phonological impairment observed in developmental dyslexia (Farmer and Klein, 1995). This hypothesis is supported by a number of studies showing evidence for impaired brief stimuli temporal processing within the auditory and visual modalities in dyslexic people. In the auditory domain, the temporal deficit hypothesis predicts that dyslexic individuals exhibit deficits in the perception of sequences of rapidly changing acoustic stimuli, typically when the interstimulus interval (ISI) is short (Tallal, 1980; Hari and Kiesila, 1996; Tallal et al., 1996; Helenius et al., 1999). Similar results have been reported in the visual modality within the framework of the magnocellular theory of developmental dyslexia (Livingstone et al., 1991; Lovegrove, 1993; Stein and Walsh, 1997; Stein, 2003). However, the deficits mentioned have been raised into question in both the auditory (Nitrour, 1999; Marshall et al., 2001; Chiappe et al., 2002) and the visual modality (Spinelli et al., 1997; Ben-Yehudah et al., 2001; Amitay et al., 2002; Bretherton and Holmes, 2003). In addition, studies have shown that dyslexic participants are not impaired in pure auditory temporal processing tasks such as detection of interaural phase modulation (Witton et al., 1997) or inter-aural temporal cues (Hari et al., 1999). These findings led Hari and Renvall (2001) to propose that the temporal deficit in developmental dyslexia may be held up by a more crucial dysfunction, which they assumed to be sluggish attentional shifting (SAS). According to this hypothesis, when dyslexic individuals deal with rapid stimuli sequences, their automatic attention system cannot disengage fast enough from one item to the next, yielding degraded processing. SAS is supposed to distort cortical networks, more specifically those which support phonological representations. Thus, the phonological deficit in developmental dyslexia would be the consequence of an attentional deficit. Hari and Renvall (2001) moreover postulate that SAS affects all sensory modalities. Reviewing a series of studies they argued that dyslexic participants showed impaired performance in both modalities (Hari and Kiesila, 1996; Hari et al., 1999, 2001; Helenius et al., 1999). Their conclusion however, was that of an amodal disorder, based on evidence from different modality-specific experimental paradigms and from different groups of dyslexic participants. Such a claim would require demonstrating that the same dyslexic individuals have impaired performance on attentional shifting tasks in different modalities.

Although they did not straightforwardly address the role of attentional processing, several studies focused on the amodal temporal perceptual deficit hypothesis (Laasonen et al., 2001; Meyler and Breznitz, 2005). Their results suggest that the disorder is not modality specific but rather extends over several modalities as expected by Hari and Renvall (2001). Only one study directly addressed the amodality assumption of the SAS theory. Using the same lateralized cued detection task paradigm in vision and audition, Faccoetti et al. (2005), concluded that visual and auditory attentional captures are both sluggish in children with developmental dyslexia. However, the disorder was observed in dyslexic children whose phonological skills were not assessed. Indeed, as it would have been expected by the SAS theory, those children should have exhibited an additional phonological disorder.

While both visual and auditory attention deficits have been reported in developmental dyslexia as potentially responsible for the phonological disorder exhibited by dyslexic readers, another kind of visual attention (VA) disorder – referred to as the VA span deficit hypothesis (Bosse et al., 2007)– has been pointed out as typically dissociating from phonological problems. The VA span disorder was defined as a limitation in the number of discrete visual elements that can be processed in parallel in a multi-element display. With respect to reading, this disorder results in a reduction of the number of letters processed simultaneously in a letter string. VA span disorders have been reported in case studies of dyslexic children who exhibited no phonological problem (Valdois et al., 2003; Dubois et al., 2007). Group studies provided additional support that phonological and VA span deficits typically dissociate in dyslexic individuals (Bosse et al., 2007; Prado et al., 2007; Lassus-Sangosse et al., 2008). Bosse et al. (2007) demonstrated that a non-trivial number of dyslexic children exhibited a single VA span disorder that related to reading performance independently of the child phonological skills. Further evidence for the independent contribution of VA span abilities to reading performance was provided by a study conducted on large samples of typically developing children from first to fifth grade (Bosse and Valdois, 2009). However, large sample studies further showed that some dyslexic readers exhibited a double disorder (poor phonological skills together with poor VA span abilities). Because VA span abilities were not assessed in the previous studies conducted within the SAS framework and because SAS abilities were not assessed in those studies which addressed VA span abilities, the question remains whether SAS and poor VA span are independent or related disorders. Evidence for amodal perceptual attention disorders1 in dyslexic individuals who exhibit no VA span disorder but impaired phonological skills would strengthen the SAS theory which establishes a theoretical link between perceptual attention disorders and phonological problems.

The present study evaluates the amodality assumption of the SAS theory through a single-case report. The participant, LL, is an exceptionally pure case of developmental phonological dyslexia. Although dyslexic individuals as a group

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1. Introduction

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1 The term ‘perceptual attention’ here refers to those attentional processes (here automatic shifting) which directly influence perceptual processing, thus allowing information to be more efficiently (here more rapidly) processed.
typically exhibit phonological problems, only a subgroup demonstrates selectively poor performance in pseudo-word reading and poor phonological skills (Sprenger-Charolles et al., 2000; White et al., 2006). In French, Bosse et al. (2007) found that only 26% of their dyslexic participants showed poor phoneme awareness, and the phonological disorder was the only underlying disorder in only 19% of the participants. Moreover, most previous studies on developmental phonological dyslexia did not take into account the VA span capacities of their dyslexic participants. In contrast, our participant was recruited because of showing a prototypical reading and spelling pattern of developmental phonological dyslexia and a single underlying phonological disorder together with demonstrating preserved VA span.

The dyslexic participant was administered similar attentional blink (AB) tasks in vision and audition, The AB is typically attributed to an inability to rapidly reallocate attentional resources from a first target (T1) to a second target (T2) in a rapid serial presentation stream. The AB prevents any adequate processing of T2 during 400–500 msec after T1 presentation in the visual modality (e.g., Broadbent and Broadbent, 1987; Raymond et al., 1992, 1995; Duncan et al., 1994; Shapiro et al., 1994; Chun and Potter, 1995; Jolicoeur and Dell’ Acqua, 1998). As a result, the rapid serial presentation task is a useful paradigm providing important pieces of information about how attentional processes deploy in the temporal domain. Using this method, several studies have shown that dyslexic subjects exhibit a prolonged visual AB – lasting in average 600–800 msec – as compared to normal readers (Hari et al., 1999; Visser et al., 2004; Buchholz and Davies, 2007; Facocetti et al., 2008). This finding suggests that T1 captures attentional resources for longer time in dyslexic participants than control participants, in the visual modality. However, although researchers have brought evidence for an AB in the auditory modality as well (Duncan et al., 1997; Mondor, 1998; Arnell and Jolicoeur, 1999; Arnell and Larson, 2002; Tremblay et al., 2005; Vachon and Tremblay, 2005, 2006; Shen and Mondor, 2006), no study evaluated whether developmental dyslexia was further characterised by an atypical AB in the auditory modality. Such a disorder is however, predicted by the SAS theory and should be all the more expected in the auditory modality that the auditory – not the visual – SAS is supposed to deploy in the temporal domain. Using this method, several studies have shown that dyslexic subjects exhibit a prolonged visual AB – lasting in average 600–800 msec – as compared to normal readers (Hari et al., 1999; Visser et al., 2004; Buchholz and Davies, 2007; Facocetti et al., 2008). This finding suggests that T1 captures attentional resources for longer time in dyslexic participants than control participants, in the visual modality. However, although researchers have brought evidence for an AB in the auditory modality as well (Duncan et al., 1997; Mondor, 1998; Arnell and Jolicoeur, 1999; Arnell and Larson, 2002; Tremblay et al., 2005; Vachon and Tremblay, 2005, 2006; Shen and Mondor, 2006), no study evaluated whether developmental dyslexia was further characterised by an atypical AB in the auditory modality. Such a disorder is however, predicted by the SAS theory and should be all the more expected in the auditory modality that the auditory – not the visual – SAS is supposed to straightforwardly account for the phonological disorder in developmental dyslexia.

In the current paper, we assessed the amodality deficit hypothesis postulated by the SAS theory by administering two similar rapid serial presentation tasks in the visual and the auditory modalities. This study directly addresses the validity of the SAS theory since for the first time the AB is assessed in the auditory modality in a young adult dyslexic participant, LL, who exhibits a phonological disorder and poor pseudo-word reading. This prototypical phonological dyslexic participant was further chosen to have no VA span disorder. In line with the SAS theory, we expected that impaired performance in the visual AB task – revealing impaired visual attentional sequential processing – should be found in LL despite preserved VA span abilities (thus, good visual attentional simultaneous processing).

## 2. Material and method

### 2.1. Participants

#### 2.1.1. Control group

Thirty young adults, with French as native language, were included as controls for the evaluation of the AB in the visual and auditory modalities. They were undergraduate students in Psychology at either the University of Savoie (Chambéry) or the University Pierre Mendès-France (Grenoble). All were skilled readers and none reported any learning impairment for reading or spelling. They had normal or corrected-to-normal vision and normal hearing and no history of neurological or psychiatric disorders.

#### 2.1.2. The dyslexic participant: LL

The dyslexic adult who took part in this study, LL, was a 35 years old female, right-handed native French speaker. She had no history of neurological disorder and her anatomical magnetic resonance imaging was normal. Her hearing was good and she reported no severe problems in speech language development. LL had a mild myopia corrected by glasses. She was free from any history of psychiatric illness, or any medical treatment. She received conventional reading instruction when attending primary school. LL never repeated a grade but she was considered as a slow reader at school. She never received neither special help nor remediation for her difficulties in reading. She was research assistant at the time of testing but naïve with respect to the purpose and background of the current research. On the “Alouette Reading Test” (Lefavrais, 1965), LL achieved a reading age of 10 years 11 months, demonstrating persistence of severe reading difficulties.

In the absence of standardized tests for the neuropsychological assessment of young adults in French, our dyslexic participant, LL, was given original tasks designed for the purpose of the current study. Her reading and spelling abilities were assessed together with her phonological skills and her VA span abilities. Her performance on the Raven Standard Progressive Matrices (Raven, 1960), verbal short-term memory, reading, spelling, phonological and VA span tasks was compared to that of 20 chronological age matched skilled readers. For each task, modified t-tests (Crawford and Howell, 1998) were carried out to compare the performance of LL with that of the control group. Scores of the dyslexic participant are provided in Table 1 together with the mean scores (and standard deviations) of the control group.

Results show that LL’s non-verbal IQ was normal. Her verbal short-term memory performance did not differ significantly from that of skilled readers in both forward and backward digit spans, despite a trend for poor working memory skills. With respect to reading, LL performed within the normal range for both irregular word and pseudo-word reading accuracy. She read both types of items more slowly than the control readers but the difference only reached significance for the pseudo-words $t_{\text{modified}(19)} = -2.33$, $p < .05$. She otherwise demonstrated very good knowledge of grapheme-phoneme conversion rules.
LL was further asked to spell 80 words – 40 regular words (e.g., /kameRa/ → caméra; /dRam/ → drame) and 40 irregular words including one or several phonemes associated to infrequent graphemes (e.g., /ane/ → harnais, /solane/ → solennel; /kwane/ → couenne) – and 40 legal (2–4 syllables long) pseudo-words. As shown in Table 1, LL’s spelling performance was similar to that of skilled readers for the real words whatever their regularity but she performed below the norm was significantly lower than the controls on the spoonerism and pseudo-word repetition tasks only (for both t-values, ps < .05).

The participant undertook three tasks of global and partial letter-string report inspired from those previously used by our team to assess VA span abilities in control and dyslexic children (Valdois et al., 2003; Bosse et al., 2007; Prado et al., 2007; Lassus-Sangosse et al., 2008; Bosse and Valdois, 2009). The tasks were adapted for the assessment of young adults by either reducing presentation time or increasing letter-string length. In all three tasks, stimuli were random consonant strings presented in upper-case in black on a white background. At the start of each trial, a central fixation point was displayed for 1000 msec followed by a blank screen for 50 msec. A letter string was then briefly presented horizontally, centred on the fixation point. In the 5-letters global report task, the 20 letter strings (e.g., R H S D M) were displayed for 100 msec, immediately followed by a mask (a series of 5 asterisks). In the 6-letters global report task, the 24 letter strings (e.g., B F D S L R) were displayed for 200 msec without mask. In the two tasks of global report, the participants had to recall as many letters as possible (identity not location) immediately after their presentation. In the partial report task, 72 6-letter strings were displayed for 200 msec. At the offset of the letter string, the cue – a vertical bar – appeared for 50 msec under one of the letters. The participants had to report the cued letter only. In each task, scores correspond to the total number of accurately (identity not location) reported letters. LL was found to score within the normal range on all three VA span tasks (for all t-values, ps > .05).

To summarize, neuropsychological assessment revealed that LL’s performance in reading and spelling was characterised by slowed pseudo-word reading rate and poor pseudo-word spelling. Her performance pattern suggests selective impairment of the analytic spelling procedure and some weakness of the analytic reading procedure, as typically reported in well compensated phonological dyslexics. Her reading pattern is typical of developmental phonological dyslexia in more transparent languages than English in which pseudo-word reading speed is typically reported as impaired whereas reading accuracy is preserved (see Wimmer, 1993 for German and Sprenger-Charolles et al., 2000 for French; or Share, 2008 for a critical review). Assessment further revealed poor pseudo-word repetition and poor phoneme awareness skills, thus reflecting an underlying phonological disorder. In contrast, LL showed normal simultaneous processing of letter strings, thus suggesting preserved VA span abilities. Overall, LL is a very pure case of developmental phonological dyslexia, characterised by poor pseudo-word reading and spelling performance and an underlying phonological disorder. More importantly, LL does not suffer from any VA span disorder making her case particularly relevant to study the impact of phonological disorder on amodal sequential attentional processing in developmental dyslexia.

Table 1 – Performance of LL, in reading, spelling, phonological tasks and VA span tasks as compared to chronological age controls (n = 20).

<table>
<thead>
<tr>
<th>Task</th>
<th>LL Performance [T value]</th>
<th>Controls Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raven matrices (raw score)</td>
<td>54 [-.05]</td>
<td>54.20 (3.8)</td>
</tr>
<tr>
<td>Verbal short-term memory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digit span forward</td>
<td>6 [-.09]</td>
<td>6.58 (1.16)</td>
</tr>
<tr>
<td>Digit span backward</td>
<td>3 [-1.35]</td>
<td>5.41 (1.73)</td>
</tr>
<tr>
<td>Phonological processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudo-word repetition (t/92)</td>
<td>83 [-3.13]*</td>
<td>89.45 (2.01)</td>
</tr>
<tr>
<td>Phonomere segmentation (t/28)</td>
<td>14 [-1.62]</td>
<td>21.90 (4.74)</td>
</tr>
<tr>
<td>Spoonerisms (t/10)</td>
<td>1 [-5.22]*</td>
<td>8.50 (2.4)</td>
</tr>
<tr>
<td>VA span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global report – 5-letters (t/100)</td>
<td>58 [-.92]</td>
<td>73.10 (16.01)</td>
</tr>
<tr>
<td>Global report – 6-letters (t/144)</td>
<td>115 [-.30]</td>
<td>119.75 (15.49)</td>
</tr>
<tr>
<td>Partial report – 6-letters (t/72)</td>
<td>48 [-1.40]</td>
<td>54.20 (7.17)</td>
</tr>
</tbody>
</table>

Note: GPC: grapheme–phoneme conversions. The asterisk (*) indicates a significant difference at p < .05 between LL and the control group.
2.2. Apparatus and stimuli

As is usual in the experimental condition, the AB was measured with a dual task procedure consisting of two targets: the first one (T1) to be identified and the second (T2) to be detected. A single condition was further administered in which the participants only had to detect T2. It served as a control condition to ensure that the participants were able to correctly process T2 when it was not preceded by the identification of another target.

2.2.1. The Visual AB task

The stimuli were black or red digits (1–9) – 12 Arial font subtending approximately .7° of visual angle – presented on a grey (192, 192, 192) background. The digits were displayed in rapid serial visual presentations in the same location at the centre of the screen. The target to be identified (T1) was the only red digit in the stream and it was either a “1” or a “5”. The target to be detected (T2) was a “0” and it was black as the distracters. Thus, T1 differed qualitatively from the set of distracters by a colour change. Each digit was exposed for 40 msec with an ISI of 60 msec, yielding a stimulus rate presentation of 10 digits per second. Stimuli were presented using E-prime software on a PC computer running Windows 2000. The computer screen was a 17-in. and had a refresh rate of 85 Hz. The viewing distance was set to 60 cm.

2.2.2. Auditory AB task

Rapid serial auditory stimuli presentations consisted of a sequence of sounds digitally edited to 16-bit resolution at a sampling rate of 44 kHz using Sound Forge 8.0. Twenty-two pure tones were used as distracters and they were ranging from 293 Hz to 1588 Hz (293, 320, 348, 380, 415, 452, 472, 493, 515, 561, 612, 668, 728, 794, 866, 944, 1030, 1123, 1224, 1335, 1456, and 1588 Hz). A higher-pitched tone of 4000 Hz was used as T1 target. This tone was either a complex tone (square tone) or a pure tone. Thus, T1 noticeably differed qualitatively from the set of distracters (higher in pitch). T2 was a pure tone of 600 Hz belonging to the distracters’ frequency range but it was delivered at a higher amplitude level (12% of 65 dB level higher than the other stimuli). All tones lasted 40 msec (including 5 msec linear onset/offset amplitude ramps in order to prevent onset and offset clicks); they were separated by silent gaps of 60 msec, yielding a stimulus rate presentation of 10 tones per second. Stimuli were presented using E-prime software on a PC computer running the rapid serial auditory sequences binaurally through headphones (earthquake, TS 800) at approximately 65 dB sound pressure level.

2.3. Procedure

Fig. 1 illustrates the procedure for the visual (see Fig. 1A) and the auditory modality (see Fig. 1B). Each participant completed two blocks of 96 trials in each modality. Each block corresponded to a single condition (96 trials) in one modality followed by a dual condition (96 trials) in the same modality. In the single condition, no T1 target was displayed and the participants only had to decide whether T2 occurred in the stream. In the dual condition, T1 was always present and T2 occurred in half of the trials. Participants were instructed to attend to and report T1 (red digit number “1” or “5” for the visual modality and the pure or complex tones for the auditory modality) while judging whether T2 occurred or not (the black digit number “0” for the visual modality and the louder sound for the auditory modality). Each trial consisted of either 15, 19 or 23 items (digits or tones). In the dual condition, T1 always appeared within the stream (“real” position of T1). The single condition was identical to the dual condition except that T1 was omitted and replaced by a black digit or a pure tone (“virtual” position of T1). The position of T1 was randomly permuted within trials so that it appeared an equal number of times in positions 7, 11 or 15. The stimuli on a given trial were randomly generated by the computer under the constraint that the same digit or tone could not appear in the previous four positions. On a given dual condition trial, T1 was randomly chosen between the two digits 1 and 5 for the visual task and between the pure and square tones for the auditory task. For both the single and the dual conditions, eight lags...
between T1 and T2 positions, from lag 1 (no intervening items, Stimulus Onset Asynchrony (SOA) = 100 msec) to lag 8 (SOA = 800 msec), were crossed with the three serial “real” or “virtual” positions of T1, for a total of 96 trials, with 12 trials at each lag. T2 absent and T2 present trials were randomized. Thus, the experimental design of each block was as follows: 48 sequences [3 (pre-T1 fillers) × 8 (lag) × 2 (T2 presence)] presented twice. One practice block of 15 trials (where a feedback was given) was followed by the single block. The order of the tasks (visual or auditory task) was counterbalanced between subjects. For the auditory task a learning phase was conducted for each participant before beginning the test. First, a T2 learning phase was conducted to ensure that the participants differentiated the louder tone from the distracters. This training phase corresponded to 14 single condition trials. This block continued until the participant reached 75% accuracy. After this first training phase the participants were trained to identify the three different auditory targets (T2: the “louder” tone, the first T1 target: the “4000 Hz pure tone” and the second T1 target: the “4000 Hz square tone”).

The experiment was conducted in a dimly lit room. The experimenter initiated each trial by pressing the space bar on the computer keyboard. Then, a cross lasting 500 msec appeared at the centre of the monitor screen for fixation. One hundred milliseconds after the offset of the fixation cross the stream of stimuli were presented successively at the centre of the screen (visual task) or binaurally through the headphones (auditory task). At the end of the trial, the experimenter had to press the space bar on the computer keyboard to continue the experiment. Immediately after each trial, participants were instructed to report aloud whether T2 was present or not (“yes” answer or “no” answer). In the dual condition, they had to name T1. The experimenter entered the responses on the computer; no feedback was given.

3. Results

3.1. Single conditions

For the two single conditions (visual and auditory), mean target detection accuracy was calculated for each virtual lag for the dyslexic participant and for the control group. Three control subjects were excluded because of their poor ability to detect T2 (with a score 2 standard deviations below the average in either the visual or the auditory modality). Table 2 provides T2 detection accuracy scores (for the present trials) as a function of lag for both the control group and the dyslexic participant in the visual and the auditory modality.

First, performance was high in the single conditions for both the control group (mean accuracy of 91% and 86% in the visual and auditory tasks, respectively) and LL (94% and 100%). The participants thus demonstrated very good abilities for identifying a single target in both the auditory and visual rapid serial presentation streams. The decline of performance observed at lag 8 for the control group in the visual condition might reflect the drop of sustained attentional resources, leading them to omit the target when it appeared at the end of the stream. For each single condition (visual and auditory), modified t-tests (Crawford and Howell, 1998) were carried out to compare the performance of LL with that of the control group at each lag. LL performed as well as the controls (all ps > .05) in both the visual and the auditory modality, except for virtual lag 5 (p < .05) in the visual condition. A ceiling effect characterised LL performance in the auditory modality and only one control participant performed as well as LL, in this task. As LL largely conformed to the control group performance, we chose to consider performance of the control group as the baseline on which to compare LL’s scores in the dual conditions.

3.2. Dual conditions: AB assessment

There is evidence for an AB when the detection of T2 is significantly lower in the dual condition (in which subjects have to identify T1 first) than in the single condition according to the position of T2 (lag) in the stream. Thus, a significant condition by lag interaction is the signature of the AB. Statistical analyses were conducted on those trials for which T1 was accurately identified. This corresponded to 98% of the trials in each modality for the control participants. The dyslexic participant accurately identified 99% T1 targets in vision and 100% in audition. Table 3 provides T2 detection accuracy rates (when T1 was well reported) as a function of lag for the control group and the dyslexic participant.

3.2.1. The control group

For each modality, an Analysis of Variance (ANOVA) with condition (single, dual) and lag (1, 2, 3, 4, 5, 6, 7, 8) as within-subjects factors was carried out on T2 detection rate. In both the visual and the auditory modalities, significant main effects of lag [vision: F(7,182) = 29.37, p < .001; audition: F(7,182) = 13.54, p < .01] and condition [vision: F(1,26) = 15.32, p < .01; audition: F(1,26) = 11.43, p < .01] were found. T2 detection was easier in the single condition than in the dual condition for the visual (90.8% vs. 83.7%) and the auditory (86.3% vs. 79.8%) modalities, suggesting greater difficulty when two targets had to be processed. In the visual modality, the condition by lag interaction was significant [F(7,182) = 16.30, p < .001]. Post-hoc comparison analysis (Newman–Keuls) showed that the control group performed significantly lower
in the dual than in the single condition at lags 1, 2, 3 and 4 (all \(p < .05\)). Control participants thus exhibit a visual AB width for approximately 400 msec following T1. In the auditory modality, a significant condition by lag interaction was also found \(F(7,182) = 3.11, p < .01\). Post-hoc comparison analyses (Newman–Keuls) showed that the condition effect was significant at lags 1 and 2 (all \(p < .05\)) corresponding to an auditory AB width of approximately 200 msec.

### 3.2.2. Case LL

It is first noteworthy, as shown on Fig. 2, that LL curve patterns differ from those of the controls in the dual condition for both modalities, even if the difference is stronger in the auditory modality in which LL shows a sharp drop of performance with lag. For each modality and each lag, modified t-tests were carried out to compare LL’s performance in the dual condition with performance of the controls in the single condition. In the visual modality, LL’s performance was impaired at lags 1, 2, 3, 4, 5, and 6 (all \(p < .05\)). She only reached control performance at lag 7 (\(p > .05\)). This indicates that LL exhibits a visual AB prolonged up to 600 msec after T1 apparition, thus 200 msec longer than for the controls. In the auditory modality, LL’s performance was impaired at lags 1 and 2 (both ps < .05) but she performed as the controls from lag 3 upwards. This result indicates that LL exhibits an auditory AB lasting 200 msec after T1 apparition, thus similar in length to the controls. However, when focusing on the sequential processing of two successive lags for the control group and for LL separately, data suggest that LL’s performance is characterised by a longer auditory AB as a priori expected in the framework of the SAS theory. In the control group, a statistically significant contrast was found between lag 1 and lag 2 \((p < .05)\) whereas no such difference was found later on \(\text{between lags 2 and 3, lags 3 and 4, lags 4 and 5, lags 5 and 6, lags 6 and 7 or lag 7 and 8 (all ps > .05)}\). These results suggest that performance of the control group significantly improved between lag 1 and lag 2 only, thus reflecting optimal processing of the second target from a 200 msec gap. In contrast, LL’s performance was very low at both lag 1 and lag 2 (17%). Her performance did not improve at lag 2 but strongly increased (17%–80%) from lag 2 to lag 3. Therefore, LL exhibited optimal processing of the second target from a 300 msec gap only, thus 100 msec later than for the controls. This later result might reflect prolonged auditory AB in LL as compared to the control group.

Finally, we analysed and compared the AB amplitude (cost of the dual condition) in the controls and in LL to assess in what extent the identification of T1 had a negative impact on T2 detection. Modified t-tests were used to compare differences in performance between the single and dual conditions in LL and the control group at each lag and for each modality. In the visual modality, no significant difference was found between LL and the controls at any lag (all ps > .05). The analysis however, revealed a tendency for deeper in amplitude visual AB, at lag 1 \([t_{\text{modified}}(26) = 1.89, p = .07]\) and lag 3 \([t_{\text{modified}}(26) = 2.03, p = .053]\) in LL. In the auditory modality, the AB amplitude was significantly deeper in LL than in the controls at lags 1 and 2 (both ps < .05). It thus clearly appears more difficult for LL than the controls to process a second target that was displayed during the blink period, in the auditory domain.

<table>
<thead>
<tr>
<th>Dual condition: lag</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual task Mean</td>
<td>82.1</td>
<td>67.0</td>
<td>79.9</td>
<td>83.5</td>
<td>92.3</td>
<td>95.1</td>
<td>96.7</td>
<td>73.5</td>
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<tr>
<td>SD</td>
<td>19.2</td>
<td>29.9</td>
<td>17.2</td>
<td>15.4</td>
<td>14.4</td>
<td>8.9</td>
<td>8.4</td>
<td>19.1</td>
</tr>
<tr>
<td>LL</td>
<td>50*</td>
<td>33*</td>
<td>50*</td>
<td>67*</td>
<td>83*</td>
<td>80*</td>
<td>100</td>
<td>67</td>
</tr>
<tr>
<td>Auditory task Mean</td>
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<td>73.1</td>
<td>74.1</td>
<td>79.3</td>
<td>85.6</td>
<td>90.9</td>
<td>86.3</td>
<td>89.6</td>
</tr>
<tr>
<td>SD</td>
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<td>23.6</td>
<td>23.9</td>
<td>24.3</td>
<td>22.6</td>
<td>13.4</td>
<td>17.6</td>
<td>15.7</td>
</tr>
<tr>
<td>LL</td>
<td>17*</td>
<td>17*</td>
<td>83</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>83</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3 – Percentage of T2 detection (when T1 was well reported) in the dual conditions as a function of lag for the control group and the dyslexic participant LL.

Note: digits in italic indicate lags for which an AB was observed in the controls. The asterisk (*) indicates a significant difference at \(p < .05\) between the dual condition in LL and the single condition in the control group (\(n = 27\)).
4. Discussion

As expected, the control group in the current study was blind to the second to-be-detected visual target when it was presented within 400 msec after the first to-be-identified target. The estimated width of their AB thus conforms to that typically reported in the visual modality (from 400 msec to 600 msec; Raymond et al., 1992; Hari et al., 1999). In the same way, an AB of 200 msec was found in the auditory modality, well in accordance with previous findings (Shen and Mondor, 2006). As previously reported in dyslexic individuals (in adults: Hari et al., 1999; or Buchholz and Davies, 2007; and in children: Visser et al., 2004, or Faccoetti et al., 2008), LV visual AB was 200 msec longer than in the controls, suggesting prolonged visual attentional dwell time (Duncan et al., 1994; Hari et al., 1999; Ward et al., 1996), thus a difficulty to disengage her attention from the first to-be-identified target.

This prolonged visual AB suggests a difficulty to process rapidly presented visual material in a participant, LL, who otherwise exhibits phonological processing difficulties which might be expected to more straightforwardly relate to an auditory processing disorder. This finding is however, consistent with Lum et al. (2007)’s study showing a prolonged and deeper visual AB in adolescents with specific language impairment. Such a co-occurrence of language/phonological problems and prolonged visual AB would be expected only in the context of an amodal SAS, affecting both the visual and the auditory modalities. Accordingly, the SAS amodality hypothesis (Hari and Renvall, 2001) predicts that LL should further exhibit an atypical AB in the auditory modality. As expected, we found that LL’s performance was far from normal in the auditory modality but it differed from that observed in the visual modality and was primarily characterised by a deeper in amplitude rather than prolonged AB. However, as in vision, her auditory deficit obviously resulted from the task constraint to process two successive rapidly presented auditory targets since LL demonstrates top-level abilities when asked to detect T2 targets in the absence of T1. Thus, deeper amplitude of the auditory AB in LL obviously corresponds to the cost of the dual condition compared to the single condition on T2 detection performance.

This study is the first report of auditory AB data in developmental dyslexia and for the first time the AB was here investigated in both the auditory and the visual modality. Although atypical AB patterns were found in both modalities in LL, these patterns substantially differed from one modality to the other, thus questioning whether performance reflected similar SAS in both modalities. At this point, we have to take into account that the visual and the auditory modalities strongly differ in temporal processing and that the AB tasks when used in these two modalities did not necessarily give rise to the same results, even in control individuals. The auditory system has a much better temporal resolution than the visual system. This is a first general issue which could have yielded differences in the expression of the visual and auditory AB deficits in LL (Vachon and Tremblay, 2008). For example, it might be assumed that our lag duration (100 msec) was too long to highlight a temporal deficit in the ‘rapid’ auditory system. Thus, even in a pathological context, a prolonged AB might not have been reflected by a T2 deficit spreading up to later lags. Perhaps it is that more sensitive variables should be looked at to highlight such a deficit in the auditory modality.

Moreover, a shorter AB is typically reported in the auditory modality when pure tones are used (Shen and Mondor, 2006; Vachon and Tremblay, 2005, 2006) as compared to the visual modality, and our own findings reveal a lag 1 sparing effect in the visual modality but not in the auditory modality for the controls as for LL. This latter asymmetry has been already noted in the literature (Tremblay et al., 2005; Shen and Mondor, 2006; Vachon and Tremblay, 2006). Lag 1 sparing refers to the finding that T2 visual detection is only slightly impaired when it is temporally adjacent to T1 (at lag 1) as compared to the maximally impaired T2 detection at lag 2 when T1 and T2 are separated by an intervening distracter. This result has been explained in terms of sluggish attentional gate that opens for T1 but then closes slowly, thus allowing T2 to gain access to processing when immediately following T1. However, even in the visual modality, the lag 1 sparing effect is abolished under some specific experimental conditions. In their review of AB studies, Visser et al. (1999) found that lag 1 sparing never occurred when T1 and T2 were presented in different spatial locations (see also, Visser et al., 2004). In our study and for the visual modality, T1 and T2 at lag 1 appeared at the same spatial location so that they fell into the same visual attentional capture, thus yielding simultaneous processing of the two targets. Tremblay et al. (2005) proposed that the same rule applies to the auditory modality except that the spatial distance in vision would correspond to the pitch distance in audition. Accordingly, a lack of lag 1 sparing in the auditory modality might have been caused by the cost of reallocating attention to different frequency ranges (from 4000 Hz for T1 to 600 Hz for T2) in a very short time (100 msec). Accordingly, the auditory AB task might have required sequential processing of the targets from lag 1 due to rapid shifting from a high-pitch tone to a low-pitch tone instead of simultaneous processing as in the visual modality.

Obviously, our statistical results primarily reveal a deficit in depth in LL’s auditory AB. However, when focusing on sequential processing differences between successive lags for the control group and for LL, LL was found to exhibit optimal processing of the second auditory targets from lag 3, thus 100 msec later than the controls. Her performance thus suggests both deeper and prolonged AB in the auditory modality.

Interestingly, this sequential deficit was also highlighted by Helenius et al. (1999) in young adults in an auditory stream segregation task, and interpreted as evidence for an auditory attentional shifting deficit by Hari and Renvall (2001) themselves. The auditory stream segregation task evaluated the speed that participants could disengage their attentional focus from one stimulus, in order to process the next different one. For long SOAs, sequences of alternating high (1000 Hz) and low pitch (400 Hz) tones are perceived as “connected”, whereas at short SOAs, they are perceived as segregating into two streams of different frequency (a high one and a low one). The authors found that the streams segregated at 210 msec for the dyslexic participants whereas the tone sequence was perceived as connected down to 130 msec in skilled readers. Hari and Renvall (2001) interpreted these findings as showing...
that dyslexic participants could not disengage their attentional focus as fast as control participants in the auditory modality. They claimed that aberrant segregation of sound streams in dyslexic subjects was evidence for prolonged attentional dwell time. Actually, we can assume that LL's auditory AB amplitude deficit at lag 1 and lag 2 might have been caused by a lower auditory segregation threshold as compared to skilled readers. If the auditory AB amplitude indeed reflects differences of segregation thresholds in LL and the controls, then higher AB amplitude should be observed at lag 1 as compared to the subsequent lags in the controls. Consequently, lower performance on T2 detection at lag 1 might correspond to a segregation threshold superior to 100 but inferior to 200 msec. This is consistent with Helenius et al. (1999)'s study in which segregation threshold was estimated around 130 msec. In the same line of reasoning, LL segregation threshold should occur between 200 and 300 msec here again in accordance with Helenius et al.'s findings who found that the dyslexic auditory segregation threshold occurred for a SOA of 210 msec. If the AB amplitude in the auditory modality is another manifestation of prolonged attentional dwell time then the observation of prolonged duration of the AB in the visual modality and higher amplitude in the auditory modality might be different illustrations of SAS in our dyslexic participant.

Moreover, the engagement/disengagement deficit postulated by the SAS theory of Hari and Renvall could be related to the opening/closing of the attentional gate in the model of Li et al. (2004). These authors suggest that a slower re-opening of the gate could lead to a deeper AB reflecting limited attention capacity. It seems reasonable to hypothesise that limited capacity as well as slower re-opening of the gate would prevent efficient shifting from one target to the other. In both modalities, the observed pattern suggests an attention disorder. Moreover, Cousineau et al. (2006) proposed a new analysis framework of the AB phenomenon. This analysis permits to characterize the AB according to four parameters (lag 1 sparing, width – i.e., duration – depth and amplitude). The authors showed that the width and depth parameters tightly correlated. Thus, considering only one dimension (i.e., width) apart from the others (i.e., depth) when trying to study the AB might be too simplistic. In the current paper, a wider visual AB in LL was associated with a marginally significant deeper visual AB on two of the lags at which the control group exhibited an AB (lag 1 and lag 3). Similarly, although LL's auditory AB was primarily deeper in amplitude, her improvement of successive target processing was delayed, thus suggesting prolonged AB in the auditory modality as well.

As such, the overall findings suggest that similar mechanisms were involved in both modalities, thus providing support to the SAS theory.

Overall, the current findings suggest that LL exhibits a perceptual attention disorder characterised by prolonged attentional dwell time in both the auditory and visual modalities. It is further noteworthy that evidence for visual attentional sequential deficit was present in the absence of any visual simultaneous attentional processing disorder, thus in the context of preserved VA span abilities. These findings are in line with previous data suggesting that sequential and simultaneous visual processing do dissociate in dyslexic individuals (Lassus-Sangosse et al., 2008). Moreover, VA span disorders have been previously reported in dyslexic individuals who were free from phonological problems (Bosse et al., 2007). It has also been demonstrated that VA span abilities primarily contribute to irregular word reading in typically developing children (Bosse and Valdois, 2009). At the theoretical level and by reference to the multitrace memory model of reading (Ans et al., 1998), a VA span disorder is expected to primarily affect the acquisition of specific orthographic knowledge (Valdois et al., 2004). A reduced VA span would thus primarily result in poor irregular word reading performance. The current data extend previous findings in suggesting that poor VA span and SAS are distinct disorders. However, a definite conclusion about the independence of these two disorders based on a single-case study would certainly be premature and, future studies on larger samples of dyslexic children would be required before concluding.

SAS characterised by poor spatial (Facoetti et al., 2006) and non-spatial (Facoetti et al., 2008) visual attentional orienting abilities has been reported in dyslexic individuals with phonological problems. This disorder was found to predict pseudo-word reading performance after controlling for phonological skills (Facoetti et al., 2006). Accordingly, Facoetti et al. hypothesised that visuo-spatial attention was involved in the analytic procedure of reading independently of phonological mechanisms (see Perry et al., 2007 for a theoretical account). In line with this account, SAS in the visual modality was found to co-occur with selectively poor pseudo-word reading in our dyslexic participant. The current data thus suggest that two kinds of attention disorder might independently contribute to reading acquisition. Thus, sluggish visual attentional shifting would more specifically relate to analytic processing and pseudo-word reading through graphemic parsing. In contrary Bosse and Valdois (2009) recently showed VA span would primarily contribute to global processing and irregular word reading in allowing the whole sequence of input words to be processed simultaneously. However, evidence for a direct link between sluggish visual attentional shifting and pseudo-word reading is only supported by some data and additional studies are required to firmly establish this relationship while excluding the additional and well documented impact of the phonological disorder on pseudo-word reading. In addition, a theoretical link has been established between VA span abilities and pseudo-word reading (Valdois et al., 2004, 2006). This link, which dissociates from phonological abilities, is supported by empirical data from groups of normally developing (Bosse and Valdois, 2009) and dyslexic children (Bosse et al., 2007). Future studies are needed to clarify the relevant impact of VA span and visual attentional shifting abilities on pseudo-word reading.

5. Conclusion

For the first time the magnitude of the AB was simultaneously measured in the visual and the auditory modalities in a young adult phonological dyslexic participant, who further showed normal VA span abilities. Our purpose was to assess the amodal hypothesis of the SAS theory of dyslexia, proposed by Hari and Renvall (2001), together with investigating whether
visual attentional shifting and VA span abilities are independent mechanisms. The investigation revealed two different kinds of deficits – a prolonged AB in the visual modality and an increase in amplitude AB in the auditory modality – that were interpreted as reflecting prolonged attentional dwell time in both modalities. Accordingly, the current findings are direct evidence for an amodal disorder affecting rapid processing of stimulus sequences in developmental dyslexia as postulated by the SAS theory. Furthermore, this amodal disorder was reported in a dyslexic participant with a phonological disorder, in accordance with the SAS theory hypothesis that sluggish shifting of auditory attention might contribute to difficulties in achieving phoneme awareness and in the acquisition of literacy. Moreover the visual AB deficit was found independently of any VA span disorder, suggesting that these two types of attentional processing can dissociate and might independently contribute to developmental dyslexia. Additional studies conducted on homogeneous groups of dyslexic individuals with and without phonological or VA span problems are required to better define the scope of the SAS theory.

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