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EYE MOVEMENT PATTERNS OF DOWN SYNDROME READERS DURING SENTENCE PROCESSING: AN EXPLORATORY STUDY

Nathalie Zardan & Cheryl Frenck-Mestre

Abstract

Eye movements were recorded in a group of Down syndrome (DS) readers as they processed sentences of differing lexical and syntactic complexity. The pattern of eye movements during reading was in line with comprehension scores and moreover revealed differences in processing that comprehension scores alone did not. Future research in DS readers with this methodology is both warranted and encouraged.

Keywords: Down syndrome, eye movements, reading.

Résumé

Lors de cette étude, nous avons enregistré les mouvements oculaires de lecteurs atteints de trisomie 21 pendant qu'ils lisaient des phrases comportant différents niveaux de complexité lexicale et syntaxique. Nous avons remarqué en premier lieu que les patterns des mouvements oculaires pendant la lecture étaient corrélés avec les performances observées dans une tâche de compréhension mais, qui plus est, mettaient en évidence des différences de traitement que la tâche de compréhension seule ne révélait pas. Ces données préliminaires militent en faveur de plus amples développements parmi cette population grâce à l'utilisation de ce dispositif.

Mots-clés : Trisomie 21, mouvements oculaires, lecture.

ZARDAN, Nathalie ; FRENCK-MESTRE, Cheryl (2007), Eye movement patterns of Down syndrome readers during sentence processing: An exploratory study, *Travaux Interdisciplinaires du Laboratoire Parole et Langage*, vol. 26, p. 179-203.

1. Introduction

Until fairly recently, children with Down syndrome (DS) were often not given the opportunity to learn to read on the premise that their cognitive disability would preclude any successful outcome (Connors, 1992). It is now recognized, however, that many of these individuals can acquire reading skills and in some cases to a relatively advanced level (Boudreau, 2002 ; Buckley & Sacks, 1987 ; Byrne, Buckley, MacDonald, & Bird, 1995 ; Byrne, MacDonald & Buckley, 2002 ; Chapman, Schwartz & Kay-Raining Bird, 1991 ; Chapman, Seung, Schwartz & Kay-Raining Bird, 1998 ; Fowler, Doherty, & Boynton, 1995 ; Kay-Raining Bird, Cleave, & McConnell, 2000 ; Rondal, 1995 ; Sheppardson, 1994 ; Sloper, Cunningham, Turner, & Knussen, 1990). The present work is an exploratory study aimed at examining the patterns of eye-movements of DS readers as they read sentences of varying levels of lexical and syntactic difficulty.

DS individuals have a characteristic phenotype, comprising both physical and mental aspects (for more complete descriptions, see Roizen & Patterson, 2003 ; Rondal, 1995). Inasmuch as physical aspects are concerned, deficits in vision and audition are common place (*cf.* Roizen & Patterson, 2003), both of which can have a bearing on reading. Concerning vision, 80% of DS children aged 5 to 12 years are reported to have ophthalmological disorders and roughly 60% have refractive errors that necessitate corrective lenses. Among the most frequent of the visual disorders found in DS children are two that have an immediate impact on the ocular motor control necessary for effective reading (strabismus (roughly 40%) and nystagmus (20%)). Hearing loss is also frequent in DS individuals; according to Cooley & Graham (1991), 75% of this population suffers from one form or another of auditory deficit, as confirmed by more recent studies (*cf.* Roizen & Patterson, 2003). Surgical intervention, medical management, hearing aids, as well as speech therapy and the teaching of sign language are all used to help reduce the communicative difficulties posed by this deficit. Hearing loss is reported to be one of the various factors that contribute to the well-known difficulties that DS children have in phoneme acquisition (*cf.* Kumin, Councill & Goodman, 1994) and tasks requiring the identification of phonemes (*cf.* Snowling, Hulme & Mercer, 2002), which in turn may have a bearing upon reading difficulties, a question that will be taken up later in the introduction.

In relation to the cognitive effects of DS, intellectual disability is present in all individuals to varying degrees of severity (Roizen & Patterson, 2003). Developmental studies of children with intellectual disabilities have revealed that in early years (4-6 years of developmental level), those children who learn to read show sight identification and decoding skills that are essentially in line with their developmental level (*cf.* Connors, Rosenquist, Sligh, Atwell & Kiser, 2006). Later in

development, however, reading skills fall behind developmental level, with capacities at both the word level and syntactic processing being lesser than could be expected based on non-verbal intelligence scores. As concerns DS readers in particular, the same pattern has been found (Chapman *et al.*, 1991 ; Chapman *et al.*, 1998).

In a recent comprehensive study, Boudreau (2002) examined the weight of various factors that might predict literacy achievement in DS individuals. It should first be noted that considerable inter-individual variability is present in this population, both as concerns the attainment of literacy skills and the various cognitive skills necessary for such. Bearing that in mind, one of the main predictors of literacy was productive language. Research on productive language has shown that in early developmental stages, the pattern of how first words are combined and the sequence of acquisition of grammatical morphemes in DS children is apparently fairly similar to that of typically developing children, though differences do exist above and beyond the obvious one of delayed onset. At this stage, non-verbal mental age is a good predictor of syntactic production (Chapman *et al.*, 1991, 1998 ; Oliver & Buckley, 1994 ; Rutter & Buckley, 1994). Later in development, however, syntactic expression is no longer in line with non-verbal intelligence in DS children (Chapman *et al.*, 1998 ; Fowler *et al.*, 1995 ; Rutter & Buckley, 1994). Syntactic deficits are apparent in the acquisition of grammatical morphemes, the mean length of utterances (MLU) and in complexity (*cf.* Fowler, 1990 ; Rondal, 1995 ; Vicari, Caselli & Tonucci, 2000). The appearance of certain grammatical elements (pronouns, auxiliaries) is delayed or absent (Chapman *et al.*, 1998 ; Rutter & Buckley, 1994) rendering verbal expression rather telegraphic in some cases (*cf.* Rondal, 1995). In relation to other cognitive capacities, linguistic development appears to be the most affected (Fowler, 1990), although the extent of the deficit varies considerably among individuals (Oliver & Buckley, 1994 ; Rondal, 1995). On the average, the highest level of verbal production achieved in DS individuals is equivalent to Brown's third stage of development, that is, relatively short and syntactically simple constructions (Fowler, 1990 ; Rondal, 1995). Exceptions to this rule do, however, exist (Rondal, 1995). These studies on verbal production reveal results that are in line with the comparatively scarce data available on reading in this population (*cf.* Boudreau, 2002).

Indeed, far fewer studies have examined literacy skills than expressive language in DS individuals. With the increased number of individuals that are exposed to reading given their inclusion in main stream classrooms however, this topic has begun to receive attention. At a general level, it has been suggested that learning to read will increase not only vocabulary level and syntactic competence in DS individuals but memory capacity as well (Laws, Buckley, MacDonald & Broadley, 1995). In a longitudinal study involving 14 DS children over a period of 3.5 years, Laws *et al.* (1995) compared the linguistic and cognitive development of those children who were in a

training program and who learned to read to that of children who were not included in the program and did not acquire literacy during the study (n=7 in both cases). At the outset of the study, the two age-matched groups showed statistically indistinguishable scores on measures of non-verbal intelligence, receptive grammar and vocabulary as well as auditory and visual memory span. At the end, however, while the two groups remained indistinguishable on measures of non-verbal intelligence (both having increased their scores), there was some indication that they differed on measures related to linguistic capacities and memory. Whereas the readers showed significant increases in vocabulary, receptive grammar and memory span, the non-reading group showed no such change¹. The estimated gain for the reading group was 1 year 9 months for vocabulary level and 1 year 4 months in syntactic development. This study is important in that it clearly demonstrates the positive benefits of providing reading instruction to DS children. Nonetheless, the claim that such impacts more than literacy skills has been challenged in a more recent longitudinal study, involving a larger sample (Byrne *et al.*, 2002), thus warranting caution. Studies of reading in DS children and young adults have mainly focused on single word decoding and more specifically on the relationship between reading ability and phonological skills. Indeed, the debate currently rages in the psycholinguistic literature as to the role of phonology in accessing meaning from the printed word (*cf.* Harm & Seidenberg, 2004, for a review), undoubtedly sparking interest in this question in studies of DS readers. Many studies have shown that these individuals have difficulty on tasks that require phonological awareness, such as phoneme detection at the onset of and/or within words and phoneme deletion (*i.e.* «if you take off the /b/ from /bat/, what you have?») as well as rhyme judgments (Boudreau, 2002 ; Cossu, Rossini & Marshall, 1993 ; Evans, 1994 ; Laws & Gunn, 2002 ; Kay-Raining Bird *et al.*, 2000 ; Snowling *et al.*, 2002). At one extreme, it has been argued that DS readers completely lack phonological awareness and, moreover, that reading can occur in its absence (Cossu *et al.*, 1993 ; see also Evans, 1994). This hypothesis has been seriously challenged by the results of subsequent studies however (Byrne, 1993 ; Cardoso-Martins & Frith, 2001 ; Cardoso-Martins, Michalick, & Pollo, 2002 ; Cupples & Iacono, 2002 ; Fowler *et al.*, 1995 ; Gombert, 2002 ; Snowling *et al.*, 2002). At a lesser extreme, researchers have suggested that even though DS readers may have phonological awareness they apparently depend more upon sight reading of learned patterns than on phonological decoding (Boudreau, 2002 ; Laws & Gunn, 2002 ; Kay-Raining Bird *et al.*, 2000). Moreover, it has been

1. It should be noted, nonetheless, that the interaction between time of testing, scores on the different measures and group was only reliable for the memory span tests. As such, some caution is warranted in concluding upon group differences.

argued that phonological skills do indeed develop in conjunction with reading in DS individuals though perhaps at a later stage (Buckley, 1994 ; Gombert, 2002 ; Snowling *et al.*, 2002) and that it can be enhanced with specific training (Connors *et al.*, 2006 ; Cupples & Iacono, 2002).

In the typical case, the reading level of DS individuals remains at a relatively early stage of development and consists of roughly 100 common words (Buckley, 1994 ; Fowler, 1990 ; Fowler *et al.*, 1995). In a recent study of word identification skills, Fidler and colleagues (Fidler, Most & Guiberson, 2005) suggested that DS readers rely heavily on visual perception to accomplish word recognition, applying visual processing strategies to a greater extent than readers with other cognitive disabilities. Systematic studies of higher levels of reading, *i.e.* at the sentence level, are lacking, due undoubtedly to the main thrust of research on reading in DS populations to date being on phonological awareness, as outlined above. The present study is an attempt to shed some light on the question of syntactic processing during reading by examining participants eye movements as they read short sentences of varying syntactic complexity.

We chose to use eye movements as a measurement of processing given the large body of data available for typically developing and skilled readers, thus providing a basis for comparison (*cf.* Rayner, 1998, for a review). Indeed, eye movements provide a multi-dimensional window into syntactic processing that is highly precise both inasmuch as the region (word) of the sentence that is under scrutiny and the timing of processing. Information in terms of the number and duration of fixations in any given region of the sentence as well as the length of saccades can be gathered for both forward-going movements (left to right saccades in scripts based on the Latin alphabet), *i.e.* when new information is processed, as well as for regressive saccades, both during the initial (first pass) reading of the sentence as well as during complete re-readings thereof. As such, the eye movement trace is a considerably richer measure of processing than can be provided by a comprehension question at the end of sentence processing.

2. The study

The present study is by definition an exploratory one in that, to our knowledge, no previous study has examined the pattern of eye-movements of DS readers. The small number of participants in our study (9 total for comprehension measures and 7 whose eye movement data could be used) also lends to the exploratory nature of this work. Our main aim was to undertake a systematic study of the measurements commonly considered in eye-movement studies of reading and to determine whether DS readers would demonstrate eye-movement patterns that revealed underlying syntactic processing and difficulty, while taking into account the obvious added factor of ocular motor difficulties quite often associated with the syndrome. The main emphasis will be

placed on the analysis of eye-movement measures related to comprehension (*i.e.* the pattern of first pass and total reading times) while also reporting other standard measures of reading (number of fixations, length of saccades and regressions). Comprehension scores were also recorded and will be examined. The design of the study allowed us to manipulate one experimental variable, which was the complexity of the sentences to be read. Sentences were of three levels of difficulty: 1) a simple declarative SVO (NVN) structure with a lexical verb, 2) the same SVO structure but with a copula and a locative preposition (NVPP), and 3) increased syntactic complexity introduced by a subject relative clause. The choice of these three levels was determined on the basis of past research, showing that while children with Down syndrome have difficulty with greater syntactic complexity (*cf.* Fowler, 1990 ; Jenkins, 1991), they successfully produce and comprehend spatial prepositions (Jenkins, 1991). Both the patterns of eye-movements during reading and comprehension scores should allow us to determine the extent to which the complexity of sentences played a significant role in reading.

3. Method

3.1. Participants

The experimental group of participants comprised nine DS adolescents and young adults (five girls), who were recruited from one of two sources (GEIST 21 des Bouches du Rhône and the Institute Mont Riant in Marseille). All nine had been pre-tested for reading ability (Test de l'Alouette) and ranged in reading level from first to third year elementary school (*i.e.* from CP to CE2, in the French system). The control group comprised nine typically-developing (TD) children, aged 6 to 9, matched in reading ability to the experimental group. The control group was tested for reading comprehension only, using the same presentation method as the experimental group but without the recording of eye-movements². For all participants, informed written consent was obtained prior to inclusion in the study, which was approved by the French ethics committee (CPP La Timone, Marseille).

2. We did not record the eye movements of TD children as the aim of the study was not to compare TD and DS children but, rather, to examine the eye movement patterns of DS readers. It should be noted that when reading for comprehension, the TD children were placed in the exact same conditions as the DS readers with the exception of not wearing the head-mounted apparatus to record eye movements.

3.2. Recording

Only the DS group was recorded during reading. Eye movements were recorded using an EyeLink II apparatus and standard software. This equipment consists of two light-weight head-mounted cameras placed directly beneath the eyes, which allows for binocular recording. During the experiment only the right eye was recorded, with a sample rate of 500 Hz. To minimize head movements and maintain a distance of 60 cm. from the screen, participants were required to maintain their chin in a Headspot (University of Houston) chin rest while reading. Prior to the experiment proper, a calibration session was performed for each participant. Sentences were presented in large type to ensure legibility (Times New Roman 36, approximately .8 cm or .75° of visual angle per character at 60 cm) on a 17" CRT monitor at a resolution of 1024 x 768 and were presented on a single line. Brightness and contrast were held constant across all participants/sessions.

3.3. Materials and design

A total of 27 experimental sentences, 9 per each of three sentence types (NVN, NVPP and subject relative clause), and 7 practice sentences (representative of the test sentences) were created for the experiment. The number of sentences was voluntarily kept low to maintain a short experimental session (roughly 30 minutes, including pauses). Sentences contained words that were of high printed frequency in French norms of elementary-school readers (Lété, Sprenger-Charolles & Colé, 2004) and which formed part of the participants' known vocabulary. Across the 27 sentences, a total of 18 lexical verbs was used in addition to the copula "to be", 35 common nouns and 9 prepositions. Simple declarative sentences were composed of an initial subject NP followed by a verb and an object NP (*e.g.* « La fille mange une pomme » *i.e.* « The girl is eating an apple »), henceforth referred to as NVN sentences. Prepositional sentences were composed of an initial subject NP followed by a copula, locative preposition and an object NP (*e.g.* « Le chat est derrière l'arbre » *i.e.* « The cat is behind the tree »), henceforth called NVPP sentences. Subject relative clause sentences contained an initial main clause followed by a subject relative clause (*e.g.* « Le garçon regarde le chat qui est debout » *i.e.* « The boy is looking at the cat that is standing up »). Pragmatics generally did not allow for comprehension of the relative clauses. Type of sentence was blocked and counter-balanced across participants, with a different random order of sentences per block for each participant.

The experiment was divided into three blocks of nine sentences each, with a short pause between blocks. Prior to the experiment a practice session was performed. Throughout the training session and experiment, the following sequence was used for each trial. A trial began with a warning tone

followed by a fixation star positioned at the left of the screen where the first word of the sentence would be presented. Once the eye was detected, the fixation star was replaced by a sentence which was presented in its entirety on a single line in the center of the screen. Each sentence was followed by the presentation of two line drawings, one on the left and one on the right half of the screen, only one of which depicted the meaning of the sentence. The position of the correct image was counter-balanced across sentences such that it was seen an equal number of times to the left and to the right of center. The sentence was presented along with the line drawings to reduce memory load for participants. Participants were requested to read the initial sentence for comprehension and to manually indicate the correct line drawing when it appeared after the initial sentence presentation. Responses were recorded manually by the experimenter.

4. Results

4.1. Comprehension accuracy

Both the typically developing (TD) and the DS group were tested on-line for comprehension. As predicted, the TD group was at ceiling level accuracy for all sentence types with little variation across participants, as shown in figure a. In contrast, the DS group showed substantial variance, particularly for the syntactically more complex sentences, as is visible in figure b. Comprehension in the DS group varied as a function of sentence type $F(2,16) = 9.21, p < .001$, with greater accuracy for all participants for the single clause sentences than for sentences containing a relative clause (84%, 84% and 63% accuracy for NVN, NVPP and relative clause sentences, respectively). Correct identification of the image that depicted the sentence ranged from 67% (6 out of 9 sentences) to 100% for single clause sentences, and from 44% (4 out of 9 sentences) to 89% (8 out of 9) for sentences containing a relative clause.

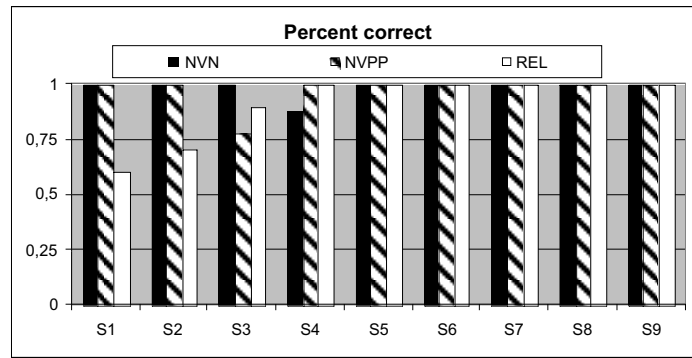


Figure a
*Comprehension accuracy in the TD group,
 plotted as a function of sentence type (NVN, NVPP, relative clause) and reader*

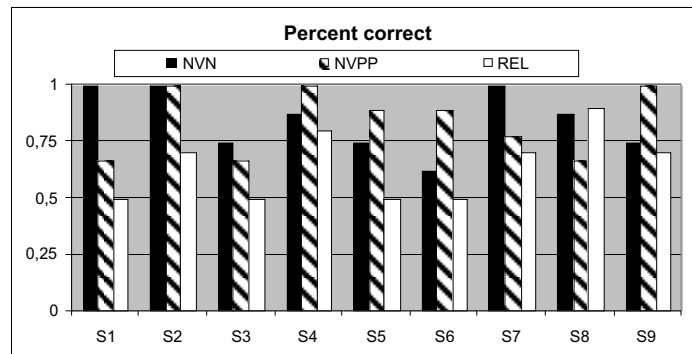


Figure b
*Comprehension accuracy in the DS group,
 plotted as a function of sentence type (NVN, NVPP, relative clause) and reader*

Statistical comparison of the TD and DS groups confirmed that comprehension was overall greater in the former ($F(1,16) = 23.96, p < .001$), however, there was also a slight trend for an interaction effect between Group and Sentence type ($F(2,32) = 2.01, p < .15$) due to there being a significantly greater difference in performance between the two groups for sentences containing a relative clause (90% vs 63% correct for the TD and DS groups, respectively, $p < .001$) than for the other two sentence types (NVN: 99% vs 84% correct for the TD and DS groups respectively, $p < .01$; NVPP: 98% vs 84% correct for the TD and DS groups respectively, $p < .01$). These effects are depicted in figure c.

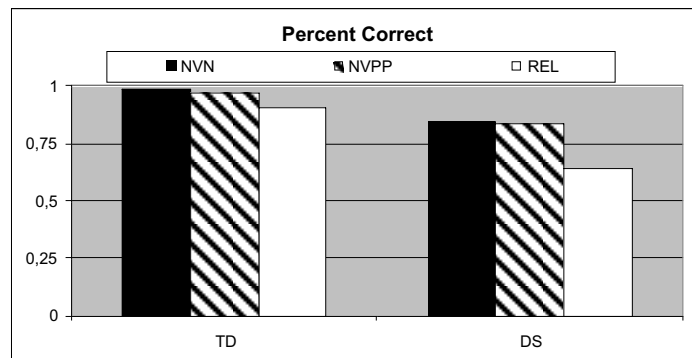


Figure c

Comprehension accuracy plotted as a function of sentence type (NVN, NVPP, relative clause) and reader group

4.2. Reading measures

Eye movements were recorded during reading for the DS group only. Analyses were performed on all sentences that were correctly understood and that passed the criteria of being read at least once in a complete left-to-right manner and that were recorded without loss of the eye-tracker³. Data for a participant were retained provided at least 1/3rd (3 out of 9) sentences could be analyzed⁴. Given these criteria, data from 7 of the 9 participants were retained for analyses for single clause sentences and from 6 participants for relative clause sentences. The percentage of sentences analyzed per participant varied from 30% to 89% per sentence type⁵, with a total of 62%, 65% and 44% of sentences analyzed for NVN, NVPP and Relative clause sentences respectively. Visual inspection of the data revealed considerable variation across participants in the eye-movement record, especially for syntactically complex sentences. For all measures, we will thus report both group means and individual means for each sentence type.

First pass gaze durations and total reading times were calculated as a function of sentence type for the different syntactic regions, with 3 regions for single clause sentences (NP1, V, NP2; and NP1, V + Prep⁶, NP2) and 5 regions for relative clause sentences (NP1, main V, NP2, relative pronoun

3. Data was lost for various reasons, due mainly to movement (difficulty in securing the head-mounted eye-tracker, overt speech during reading, *etc.*). Data that was lost due to improper reading, *i.e.* skipping haphazardly between sentence regions, accounted for approximately 10% of loss.

4. One participant was excluded because of excessive loss of data, and one because of having too few sentences for which a true left-to-right parse was performed.

5. For six of the seven participants retained, more than 50% of sentences were analyzed for single clause sentences.

6. The region of the verb was conflated to add the preposition given the very short length (3 letters) of the copula and the high probability that short regions are skipped.

+ subordinate V, end region), as depicted in the examples below. First pass gaze durations were defined as all left-to-right fixations within a region from the time the eye first entered the region prior to exiting the region to the right or left⁷. Total reading times were defined as the summation of all fixations in a region. Average fixation durations were also calculated, independent of sentence type. In addition to reading times a correlated measure, *i.e.* the number of fixations within a region, was calculated. Last, the percentage of both forward saccades (*i.e.* left to right) and regressions was computed, as well as the amplitude of forward regressions.

1. La fille / mange / une pomme.
2. Le chat / est derrière / l'arbre.
3. Le garçon / regarde / le chat / qui est / debout.

4.3. Saccades

The mean percentage of forward saccades during readers' first pass through the sentence was superior to that of regressive saccades for all sentence types (60%, 65% and 69% forward saccades for NVN, NVPP and relative clause sentences, respectively). This was true, moreover, for the majority of participants (*cf.* figure 1), although there were clearly three participants who showed a pattern of an equal percentage of forward and regressive saccades for some sentences. The mean amplitude of forward saccades in number of characters is also reported (*cf.* figure 2) however, some caution is warranted in comparing these measures to those generally reported in the literature. Indeed, the font size used in the present study was far larger than that used in standard studies such that the degree of visual angle of one character in the present study was equivalent to roughly that of three characters in standard studies of reading.

7. Although a fixation point was provided prior to presenting the sentence, many of the participants had difficulty maintaining this position such that on many trials the eye was not at the left of the screen when the sentence replaced the fixation point, necessitating a regressive saccade to begin reading at sentence onset. Rather than reject these trials, we chose to calculate "first pass" measures starting from the first fixation at sentence onset. Approximately 15% of sentences were affected by this readjustment. No more than 3 regressive saccades and in most cases only 1 or 2 were allowed at sentence onset, above which only second pass measures were considered..

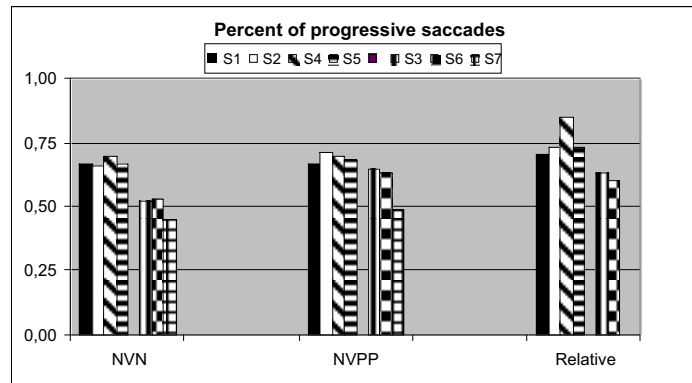


Figure 1

Percentage of forward saccades during the first pass through the sentence as a function of sentence type and participant

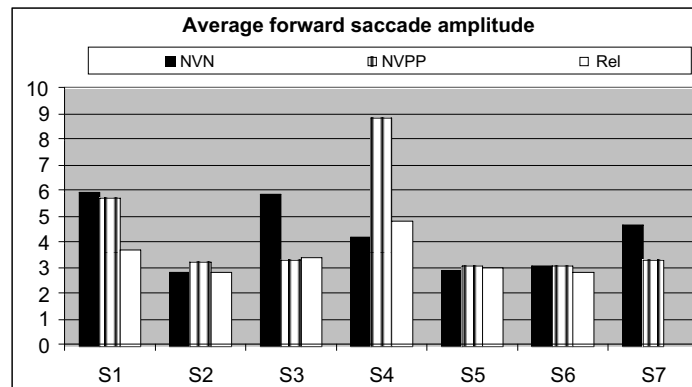


Figure 2

Average size of forward saccades in number of characters as a function of sentence type and participant

4.4. Average fixation durations

In figure 3 are reported the average fixation durations per participant, for each of the three sentence types. Overall, mean fixation duration was 277, 281 and 270 ms for NVN, NVPP and relative clause sentences, respectively, and did not differ as a function of sentence type ($F < 1$).

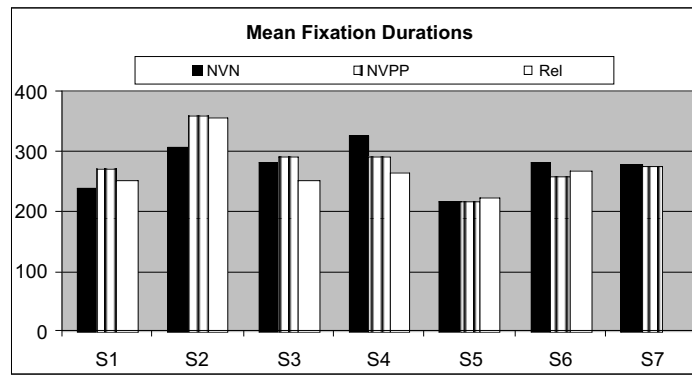


Figure 3
Mean fixation durations as a function of sentence type and participant

4.5. First pass and total reading times

The visual inspection of reading times revealed a difference in reading patterns as a function of sentence type. For single-clause NVN sentences, reading times showed an increase in duration at the final (*i.e.* third) region of the sentence compared to the initial two regions. This was true both for first pass gaze durations and total reading times. For single clause NVPP sentences, this pattern was only clearly visible for total reading times. For relative clause sentences, an increase in both first pass gaze duration and total reading times was apparent at the region where the relative clause began. To further examine this pattern, the data was analyzed separately for each sentence type.

For NVN sentences, the analysis of first pass gaze durations confirmed the difference in reading times as a function of sentence region $F(2,12) = 17.32, p < .001$, and post hoc comparisons revealed longer reading times for the final region (1083 ms) than for either the first region comprising the initial NP (885 ms), or the second region which contained the verb (607 ms). Moreover, this pattern, visible in figure 4a, was true of all but one of the seven readers (*cf.* figure 4b). The same pattern was observed for total reading times (*cf.* figure 4c), with a significant effect of sentence region $F(2,12) = 9.36, p < .005$, due to longer reading times for the final region (2097 ms) compared to the first (1495 ms) or second region (1255 ms) which did not differ significantly from each other. The pattern of the number of fixations closely matched that of reading times, with longer reading times in a region generally associated with a higher number of fixations (*cf.* figure 4d).

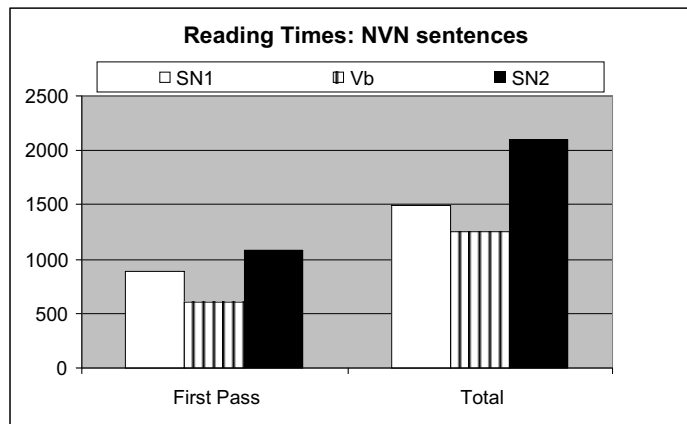


Figure 4a
Mean first pass gaze durations and total reading times for correctly interpreted NVN sentences as a function of sentence region

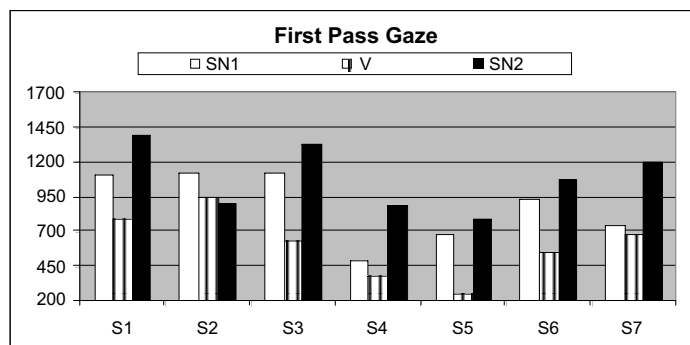


Figure 4b
Mean first pass gaze durations for correctly interpreted NVN sentences as a function of sentence region and participant

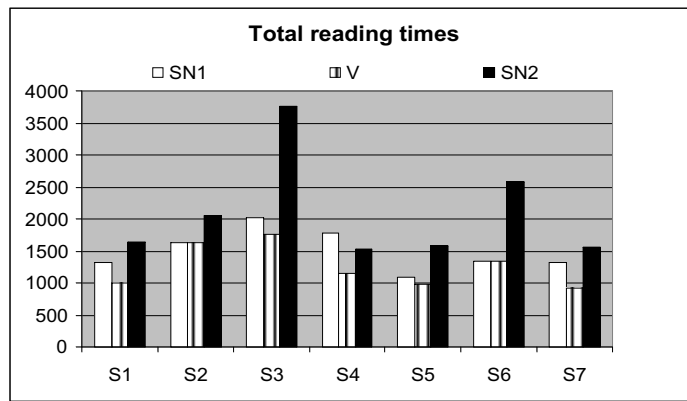


Figure 4c

Mean total reading times for correctly interpreted NVN sentences as a function of sentence region and participant

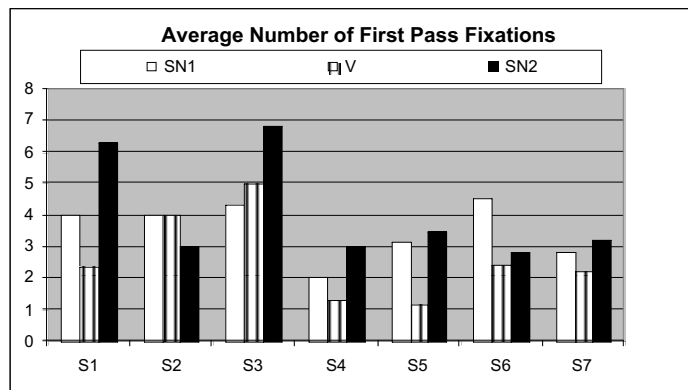


Figure 4d

Mean number of first pass fixations for NVN sentences as a function of sentence region and participant

For NVPP sentences, the analysis of first pass gaze durations did not reveal an effect of sentence region $F(2,12) = 1.47$, ns. Average reading times did not differ statistically from each other for the three sentence regions (918, 1135 and 1124 ms, for the first, second and third regions, respectively) despite a slight numerical increase for the later regions (*cf.* figure 5a). As can be seen in the data for individual readers (*cf.* figure 5b), only two participants showed an increase for the final region during the first pass through the sentence. The analysis of total reading times did, however, reveal an effect of sentence region $F(2,12) = 4.29$, $p < .04$, which was true of the majority of participants (*cf.* figure 5c). Post hoc comparisons revealed that average total reading times were statistically longer for the final region (2584 ms) compared to the initial noun of the sentence

(1550 ms), and were intermediary for the second region (2025 ms) which did not differ significantly from either the first or final region. The pattern of fixations correlated with reading times, with a greater number of fixations generally observed in conjunction with longer processing time (*cf.* figure 5d).

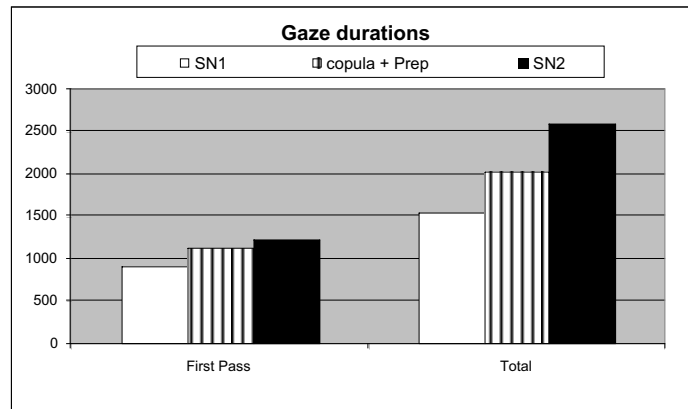


Figure 5a

Mean first pass gaze durations and total reading times for correctly interpreted NVPP sentences as a function of sentence region

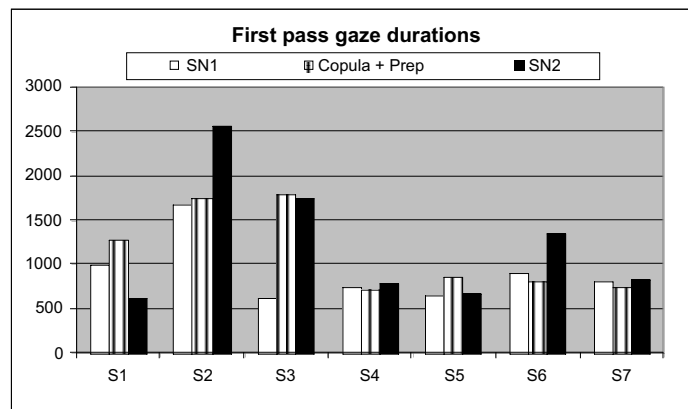


Figure 5b

Mean first pass gaze durations for correctly interpreted NVPP sentences as a function of sentence region and participant

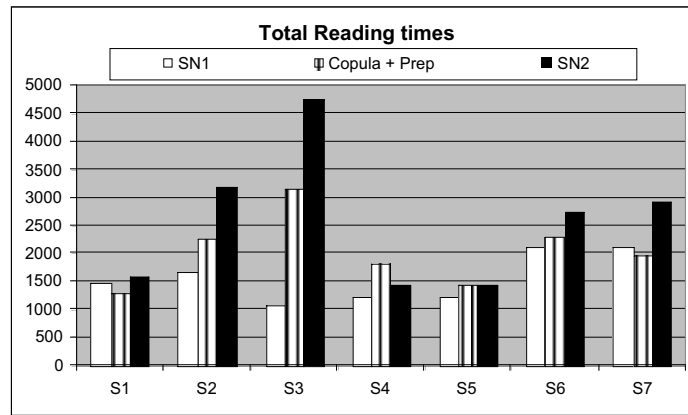


Figure 5c

Total reading times for correctly interpreted NVPP sentences as a function of sentence region and participant

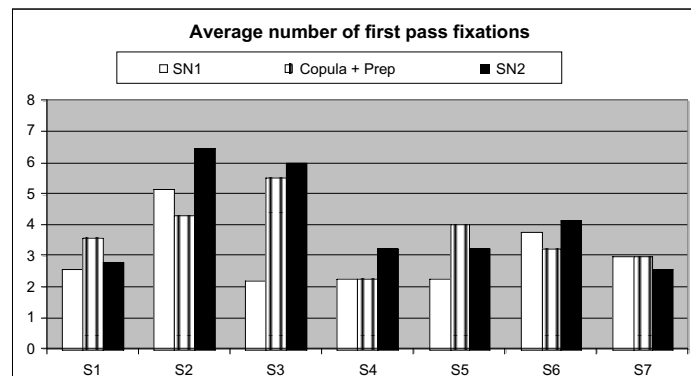


Figure 5d

Mean number of first pass fixations for NVPP sentences as a function of sentence region and participant

The analysis of eye movements for sentences containing a subject relative clause was undertaken, although caution is warranted given that a small percentage of items was considered (only 44% of sentences, total, could be analyzed). The analysis of first pass gaze durations revealed a small trend for an effect of sentence region $F(4,20) = 2.40, p < .08$, and post hoc comparisons showed trends for longer mean gaze duration at the region containing the subject relative pronoun (“qui” in French) and subordinate verb, *i.e.* at the fourth region (1234 ms), than for each of the prior three regions, namely the first noun (755 ms), main verb (935 ms) and the second noun (765 ms) which was both the object of the main verb and the head of the relative clause (*cf.* figures 6a and 6b). The

analysis of total reading times revealed a significant effect of sentence region $F(4,20) = 4.30$, $p < .01$, and post hoc comparisons showed this to be due to longer mean durations for the fourth and fifth (final) regions (2188 ms and 2308 ms, respectively) compared to the first three sentence regions (1227, 1234 and 1492 ms for the first, second and third region, respectively). Neither the last two regions nor the first three differed significantly from each other in total reading time (*cf.* figures 6a and 6c). This pattern is also visible in the number of fixations (*cf.* figure 6d).

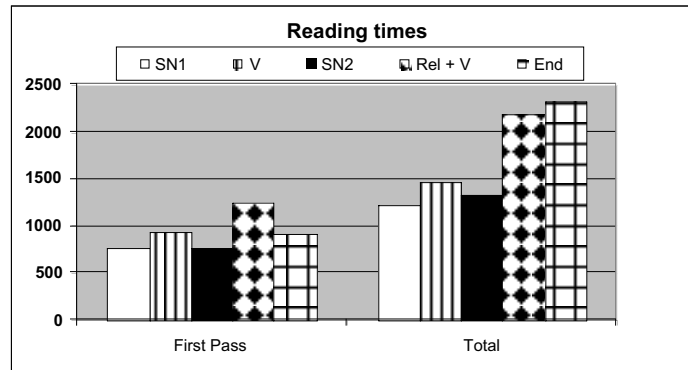


Figure 6a

Mean first pass gaze durations and total reading times for correctly interpreted relative clause sentences as a function of sentence region

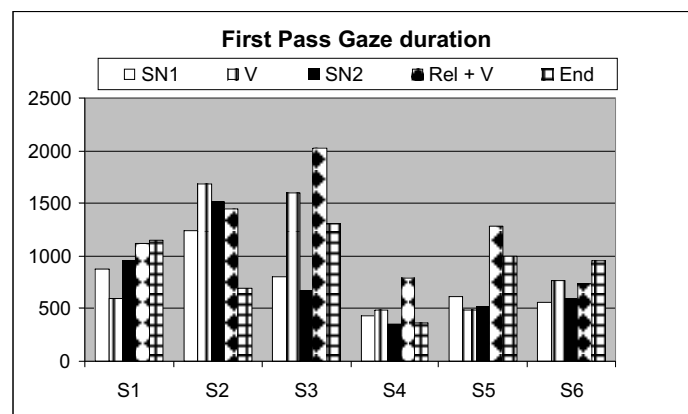


Figure 6b

Mean first pass gaze durations for correctly interpreted relative clause sentences as a function of sentence region and participant

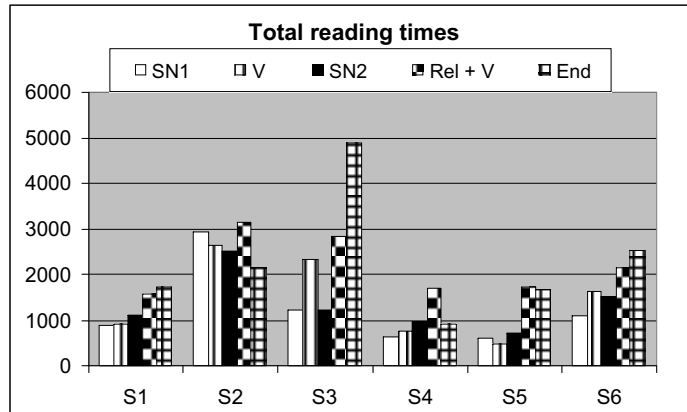


Figure 6c

Mean total reading times for correctly interpreted relative clause sentences as a function of sentence region and participant

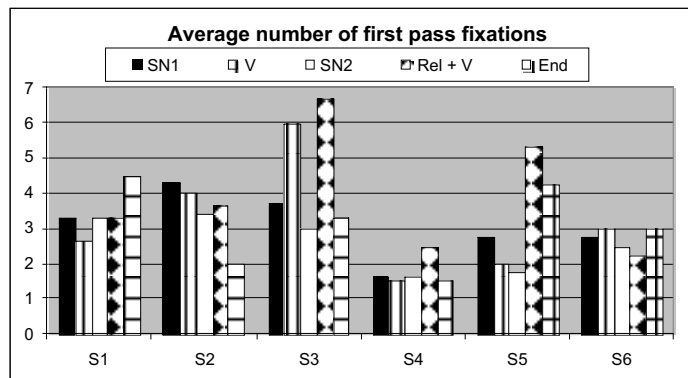


Figure 6d

Mean number of first pass fixations for relative clause sentences as a function of sentence region and participant

5. Discussion

The results of the present pilot study provide interesting and novel information in relation to the processes engaged by DS individuals when reading. Indeed, the use of eye movements in conjunction with end of sentence comprehension questions allowed us to track on-line processing in a manner that has not been attempted previously.

As a general caveat, it is important to underline that substantial inter-individual variation in performance was observed, both in comprehension scores and in the eye-movement record, and was greater for syntactically more complex sentences, *i.e.* for sentences containing a subject relative clause than for single clause sentences. This result is in line with those of previous studies, showing a considerable range in reading abilities in DS individuals (Boudreau, 2002 ; Rondall, 1995). That said, general trends were found. As could be expected, comprehension was higher for single clause sentences than for relative clauses, for which comprehension was at only 63% for the group. Nonetheless, five of the nine participants showed quite good comprehension for these syntactically more complex constructions, scoring above 70% correct, and two of the participants scored 89% (or eight out of the nine sentences). This result belies the claim that DS readers do not surpass a rudimentary level of syntactic comprehension (Fowler, 1990). Inasmuch as the syntactically simple constructions were concerned, comprehension was indeed quite high (84% overall). The pattern of eye movements during reading was in line with comprehension scores and moreover revealed differences in processing that comprehension scores alone did not.

The first measures of eye movements that we will consider are rather general measures of reading, which are the mean duration of a fixation, the ratio of forward saccades to regressions and the amplitude of saccades. From the literature we know that typical readers move their eyes forward in the text more often than backwards (in children, roughly 75% of saccades are forward going), that the average size of a saccade is from 7 to 9 character spaces and that an average fixation is roughly 250 ms for adults and for children from fourth grade on (Rayner, 1998). All of these values are subject to variation, depending on both low level factors such as luminance and physical characteristics of the text as well as higher level linguistic factors such as the frequency of words, syntactic complexity and lexical or structural ambiguity. Moreover, these measures of reading all show a developmental aspect, with longer fixations, shorter saccades and more regressions in typically developing children who are learning to read (grades 1 through 4) than in skilled adult readers (McConkie *et al.*, 1991; Rayner, 1985). In addition, more inter-individual variation is observed among children than adults (McConkie *et al.*, 1991).

For the type of materials used in the present study, average values could be expected for all of the above reading measures, with the caveat that the large font we used may have affected saccade size. As a general rule, the size of characters does not impinge upon fixation time or saccade amplitude, however this rule does not hold for extremely small or large fonts (*cf.* Rayner, 1998). The results we obtained only partially conform to standard values. Fixation durations were not appreciably longer on average than those generally observed, being roughly 275 ms. Moreover, this

was true of the majority of participants, with fairly little variation in the group⁸. For saccades, a rather mixed picture arises. On the average, the group of DS readers studied here showed 65% of forward saccades across all sentence types. This is somewhat lower than that found for typically developing children in the same grade level who on average make 75% of forward saccades (*cf.* Rayner, 1998). In addition, there was a large degree of variability in the DS group, with three of the seven participants recorded showing an almost equal ratio of forward saccades to regressions⁹. The reason for the elevated percentage of regressions we observed remains to be determined; it is quite conceivable that poorer ocular motor control is a contributing factor given the known deficits in this population. Indeed, if the reader overshoots the target, *i.e.* moves her eyes too far into the word, a short regression will be required to bring the word into the best position for all letters to be properly identified (O'Regan, 1980 ; Rayner, 1998). The level of reading skill in the DS group may well have contributed to the relatively high percentage of regressions as well. Research conducted with typical readers has revealed that when difficulties are encountered, less skilled readers make more regressive saccades than do more skilled readers due to the fact that more skilled readers are better at immediately locating the region of the sentence where difficulties arose (Kennedy & Murray, 1987). Last, we will only mention in passing the mean amplitude of saccades. The mean amplitude of forward saccades was roughly 4.5 character spaces for single clause sentences and 3.5 character spaces for relative clause sentences. These values are rather small compared to the performance of typically developing children of matched reading level (*cf.* Rayner, 1998) however, it is important to note that in a smaller font than the one we used, (for example Times 12, as opposed to Times 36, used here) the number of characters would be equivalent to roughly 13 and 10 characters. The latter average is much closer to that found in typical young readers. Whether the small saccade size was the product of the large font used in the present study or that of our readers' skills remains to be determined in future studies.

In addition to the general measures outlined above, our results also provided more specific information about reading strategies, as revealed by the pattern of reading times across the different regions of sentences. For the simplest level of sentence we used – single clause NVN sentences with SVO structure – the pattern of reading times resembled that found in typical

8. Interestingly, this was true even of the two participants whose eye movement record was too noisy to retain for analysis, suggesting a very low level basis of control of this measure.

9. For one of the participants, eye movement data was not be retained for analysis despite relatively high comprehension scores due to a rather erratic pattern of back and forth eye movements among the different sentence regions, and for another, eye movement data for relative clause sentences was not retained for the same reason.

readers, where longer reading times are found at the end of the sentence (Just & Carpenter, 1980 ; Mitchell & Greene, 1978 ; Rayner, Kambe & Duffy, 2000). This effect, known as a « sentence wrap up » effect, is generally attributed to readers' taking time at the final region of the sentence to consolidate the information they gathered and to perform reanalysis if necessary. For NVN sentences, this pattern was found in both the first pass through the sentence and in the total reading times (*i.e.* the first pass as well as all subsequent re-readings), and was observed for the majority of the participants. As such, it seems safe to conclude that our readers understood this type of sentence from the first time they read it, even if, as is often the case in typical reading, re-readings were undertaken. The high level of comprehension scores for these sentences (84%) also supports this conclusion. For single clause sentences that included a prepositional phrase (the NVPP sentences), the pattern of reading times also showed an increase at the final sentence region, however this effect was clearly visible only in the total reading times. The pattern of first pass reading times was fairly monotonic across the sentence, for the group means as well as for the majority of participants. Comprehension of these sentences was nonetheless equally as high as that for the NVN sentences. One might tentatively conclude that the inclusion of a prepositional phrase increased difficulty slightly such that more processing (*i.e.* subsequent re-readings) was necessary prior to full comprehension. Last, for sentences with a higher level of complexity – *i.e.* those containing an initial main clause followed by a subject relative clause – the pattern of reading times from the beginning to the end of the sentence revealed the same delayed effect of sentence wrap up. The pattern of first pass reading times suggested an increase in processing at the head of the relative clause, that is, the penultimate region, but not at the final sentence region. Only total reading times revealed significantly longer processing times for both the penultimate and final regions. As for the NVPP sentences, this result would suggest that for relative clause sentences full comprehension was not achieved during the first pass through the sentence but necessitated further processing and subsequent re-readings. Moreover, the pattern of reading times observed during the first pass through relative clause sentences suggests that participants may have concentrated on the main clause of the sentence during the first pass, and only truly treated the relative clause during subsequent readings of the sentence. Further investigation of the pattern of regressive eye movements for this type of sentence should allow us to verify this hypothesis.

6. Conclusions

While preliminary, given the small population that was studied, the results obtained are promising and warrant future studies of eye movements as a measure of reading comprehension in DS readers. The measures we investigated – proportion of forward saccades, mean fixation durations,

first pass and total reading times of the different sentence regions – provided a window onto how these readers process sentences on line and information that, to our knowledge, has not been previously reported for this population. Further research with a larger population and more specific research hypotheses is of course necessary to substantiate the findings reported here. We can only encourage such endeavors.

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