Eye-Movement Patterns of Readers With Down Syndrome During Sentence-Processing: An Exploratory Study

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Abstract

Eye movements were examined to determine how readers with Down syndrome process sentences online. Participants were 9 individuals with Down syndrome ranging in reading level from Grades 1 to 3 and a reading-level-matched control group. For syntactically simple sentences, the pattern of reading times was similar for the two groups, with longer reading times found at sentence end. This "wrap-up" effect was also found in the first reading of more complex sentences for the control group, whereas it only emerged later for the readers with Down syndrome. Our results provide evidence that eye movements can be used to investigate reading in individuals with Down syndrome and underline the need for future studies.

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It is now clearly established that many individuals with Down syndrome can acquire some level of literacy (Abbeduto, Warren, & Conners, 2007; Boudreau, 2002; Turner & Alborz, 2003). In the vast majority of experimental studies, researchers have concentrated, however, on understanding processing at the word level (see Groen, Laws, Nation, & Bishop, 2006). The present study is an exploratory investigation in which syntactic processing was examined using the patterns of eye-movements of readers with Down syndrome as an indicator.

Research on expressive 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 children with Down syndrome is apparently fairly similar to that of typically developing children of similar developmental level, although differences do exist above and beyond the obvious one of delayed onset (Berglund, Eriksson, & Johansson, 2001). During the first years (roughly up to mental age [MA] 2.5), nonverbal MA is a good predictor of syntactic production (Chapman, Seung, Schwartz, & Kay-Raining Bird, 1998; Oliver & Buckley, 1994; Rutter & Buckley, 1994). Later in development, however, syntactic expression is no longer in line with nonverbal intelligence in individuals with Down syndrome. Moreover, morphosyntactic development begins to lag behind vocabulary development (Abbeduto et al., 2003; Chapman et al., 1998; Fowler, Doherty, & Boynton, 1995; Rutter & Buckley, 1994; Vicari, Caselli, & Tonucci, 2000). Interestingly, this asynchrony in the acquisition of vocabulary and morphosyntax is not documented in other syndromes that cause intellectual disabilities, although syntax is indeed an area that generally poses difficulty (for discussions, see Abbeduto et al., 2001; Abbeduto et al., 2003; Price et al., 2008; Vicari, Caselli, Gagliardi, Tonucci, & Volterra, 2002). Syntactic deficits are apparent in the acquisition of grammatical morphemes, the mean length of utterances (MLUs), and complexity of sentence structure (Fowler, 1990; Rondal, 1995; Vicari et al., 2000). The appearance of certain grammatical elements (pronouns, auxiliaries) is delayed or absent (Chapman et al., 1998; Rutter & Buckley, 1994; Vicari et al., 2000), rendering verbal expression rather telegraphic in some cases (Rondal, 1995; Vicari et al., 2000). Although linguistic development is systematically affected, the extent of the deficit varies considerably among individuals, as attested by numerous studies (for reviews, see Abbeduto et al., 2007; Chapman, 2003; Roberts, Price, & Malkin, 2007). Whereas in early studies researchers reported that, on average, the highest level of expressive syntax achieved in individuals with Down syndrome was equivalent to Brown's (1973) third stage of development, that is, relatively short and syntactically simple constructions (Fowler, 1990; Fowler et al., 1995), subsequent work has provided a more promising picture. Notably, not only do exceptions to this rule exist (Rondal, 1995), but recent work has suggested that, in general, individuals with Down syndrome continue to increase in syntactic production (as measured by MLU in morphemes) throughout adolescence (Chapman, Hesketh, & Kistler, 2002; Chapman et al., 1998). Syntactic expression has also been found to be related to syntactic comprehension (Chapman et al., 1998; Chapman, Seung, Schwartz, & Kay-Raining Bird, 2000), with the greatest increase observed in individuals who do not decline in comprehension ability with age (Chapman et al., 2002). Last, the controlled study of narrative abilities, in contrast to spontaneous conversation, has shown that individuals with Down syndrome can indeed surpass simple levels of syntactic expression (Chapman et al., 1998; Miles, Chapman, & Sindberg, 2006; Thordardottir, Chapman, & Wagner, 2002). These studies on verbal expression reveal results that are consistent with the comparatively scarce data available on reading in this population.

Research on reading abilities in the Down syndrome population has been concentrated predominantly on three topics. The first of these is the impact that achieving literacy may have on intellectual development. Whereas in an early longitudinal study, Laws, Buckley, MacDonald, Broadley, and Bird (1995) suggested that children who learned to read showed increased language skills and memory capacity compared with nonreaders, this claim was subsequently called into question in a longitudinal study involving a larger sample (A. Byrne, MacDonald, & Buckley, 2002). The second topic pertains to factors that predict literacy. Recent reviews of this issue, which were predominantly focused on studies of word-level skills, have suggested that both visual and verbal memory span and expressive language are important predictors; receptive vocabulary and grammar may become more reliable predictors in adolescence and young adulthood (for discussions, see Boudreau, 2002; Groen et al., 2006). The third topic relates to the attainment of literacy and, in general, has been approached by researchers using broad measures (see Abbeduto et al., 2007; Boudreau, 2002; Turner & Alborz, 2003; Turner, Alborz, & Gayle, 2008).

Although the percentage of individuals with Down syndrome found to achieve literacy varies, comparisons across studies is rendered difficult because different testing methods, a variety of standardized tests, and varying definitions of what constitutes literacy have been used. Reading vocabulary has been estimated to consist of roughly 100 common words in most cases (Fowler, 1990; Fowler et al., 1995; Shepperdson, 1994). With regard to text comprehension, only a few researchers have reported performance level; some were case studies or rather anecdotal, making it difficult to generalize (Boudreau, 2002; A. Byrne et al., 2002; Fowler et al., 1995; Groen et al., 2006; Laws, Byrne, & Buckley, 2000; Moni & Jobling, 2001; Morgan, Moni, & Jobling, 2004). Nonetheless, these studies reveal that (a) text comprehension rarely surpasses an elementary level (roughly Grade 2), (b) is better for literal than inference-based information, (c) is less advanced than word-decoding skills, and (d) can be enhanced by special programs intended to capture the reader's interest. The capacity to identify words by sight and to read simple sentences and story books increases slightly with age and continued education in integrated schools; however, it is difficult to determine a general pattern given the considerable interindividual variability (Turner et al., 2008). At elementary levels (Grade 1), there is some evidence from a study conducted in Italian (a shallow orthography) that individuals with Down syndrome who can read do so as quickly and comprehend short passages as well as typically developing beginning readers matched on MA and isolated word reading ability (Verruci, Menghini, & Vicari, 2006, but see Boudreau, 2002, for divergent results in English). Even in exceptional cases, however, reading comprehension remains difficult compared to word identification for individuals with Down syndrome (Groen et al., 2006).

A fourth topic, which has received comparatively less attention, is how do individuals with Down syndrome actually learn to read? Investigators who have addressed this question have predominantly examined single-word decoding. The issue that has received the most attention is whether these individuals develop and use phonological skills when reading, undoubtedly influenced by the resurgence of interest in this question in typically developing children and adult populations (for a review, see Harm & Seidenberg, 2004). At one extreme, for example, Cossu, Rossini, and Marshall (1993) argued that readers with Down syndrome lack phonological awareness and that reading can occur in its absence. This hypothesis has been seriously challenged (Buckley, Bird, & Byrne, 1996; B. Byrne, 1993; Cardoso-Martins & Frith, 2001; Cupples & Iacono, 2002; Fowler et al., 1995; Gombert, 2002; Groen et al., 2006; Snowling, Hulme, & Mercer, 2002). At a lesser extreme, other researchers have suggested that although readers with Down syndrome have phonological awareness, they do not follow the same developmental trajectory as do typically developing readers (for a review see Groen et al., 2006), but depend more on visual processing or analogies than on phonological decoding (Boudreau, 2002; Laws & Gunn, 2002; Kay-Raining Bird, Cleave, & McConnel, 2000; Roch & Jarrold, 2008, but see Groen et al., 2006, for an exceptional case). In line with the latter hypothesis, in a study of word identification skills, Fidler, Most, and Guiberson (2005) reported that readers with Down syndrome rely heavily on visual perception to accomplish word recognition, applying visual processing strategies to a greater extent than do readers with other cognitive disabilities.

Our intent in the present study was to shed light on syntactic processing during reading by individuals with Down syndrome through examining participants' eye movements as they read short sentences of varying lexical and syntactic complexity. Eye movements provide a multidimensional, highly precise record of processing and have been successfully used to study reading since Tinker's (1936) seminal study. This processing measure has been widely studied during reading by adults (see reviews by Clifton, Staub, & Rayner, 2007; Rayner, 1998) and, to a lesser extent, by typically developing children (McConkie et al., 1991; Rayner, 1986), thus providing a basis of comparison for the present study. From this work we know that the eyes do not move smoothly over text but progress in short jumps, or *saccades*, which vary in size but are generally 7 to 9 character spaces (2° of visual angle) in length and tend to place the eyes in an optimal position for viewing a word, that is, slightly off-center (O'Regan, 1980; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; for a review see Brysbaert & Nazir, 2005). Readers typically move their eyes forward in the text more often than backwards; in children, roughly 75% of saccades are forward going. The average duration of a *fixation* (i.e., when the eyes momentarily stop) is roughly 250 ms for adults and for children beginning in fourth grade (Rayner, 1998, 1986). All of these values are subject to variation, depending on 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 (Clifton et al., 2007; Rayner, 1998). In general, increased processing difficulty during reading is reflected by changes in one measure or another, such as increased fixation durations, shorter saccades, or an increased proportion of regressive saccades (for a review of over 100 studies of adult readers. see Clifton et al., 2007). 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, 1986). In addition, more interindividual variation is observed among children than adults (McConkie et al., 1991).

The present study is, by definition, an exploratory one in that, to our knowledge, no previous researchers have examined the pattern of eye-movements of readers with Down syndrome. The small number of participants in our study also lends to its exploratory nature. Our main aim was to undertake a systematic study of the measurements commonly considered in eye-movement studies of reading and to determine whether readers with Down syndrome would demonstrate eye-movement patterns that reveal underlying syntactic processing and difficulty. The design of the study allowed us to manipulate one experimental variable, namely, the complexity of sentences. Sentences were of three levels of difficulty: (a) a simple declarative structure involving a subject, lexical verb, and object (SVO); (b) the same SVO structure but with a copula and a locative preposition; and (c) increased syntactic complexity introduced by an apposed subject relative clause following the main clause. The choice of these three levels was determined on the basis of offline research, showing that although individuals with Down syndrome have difficulty comprehending syntactically complex sentences (Chapman et al., 1991; Fowler, 1990; Fowler et al., 1995, but see Chapman, 2003; Thordardottir et al., 2002), they successfully produce and comprehend spatial prepositions (Jenkins, 1991).

The pattern of eye movements during reading in conjunction with comprehension scores should allow us to determine whether and, if so, when, our readers correctly understand the sentences and how this comprehension is affected by syntactic complexity. Indeed, by recording eye movements one can distinguish *first-pass processing* (i.e., the first time that the reader's eyes land on a word/sentence region) from *total reading times*, which include all fixations in a given region whether during the first reading or subsequent re-readings.

As a general rule, first-pass measures are understood to be indicative of more automatic parsing routines, whereas the latter measures provided by total reading times are more prone to strategic processes, although the demarcation is not as strict as once thought (Boland, 2004). As such, eye movements, in contrast to offline measures of comprehension, will allow us to determine when and where processing differences may occur between sentences of differing syntactic complexity. The eye-movement record will reveal where in the sentence participants hesitate, the percentage of time they spend regressing to previously read regions, the amount of time spent during the first reading versus re-readings of the sentences, and whether these measures vary as a function of complexity. Moreover, by comparing the eye-movement record of readers with Down syndrome to that of reading-level-matched typically developing readers, we can provide a first glimpse of how these groups do or do not differ in their reading behavior.

To our knowledge there are no published studies on the eye-movement record of typically developing children of different reading abilities. Studies of adult readers of differing reading skills (Clifton et al., 2007; Kennedy & Murray, 1987), however, allow us to make several hypotheses about how the eye-movement record may differ for readers with Down syndrome and typically developing readers. Note, first, that the comparison of these two groups poses a challenge. Indeed, although one can match readers on reading level at Grades 1 though 3, the number of years that readers with Down syndrome will have spent reading (whether isolated words or text) will be higher in almost all cases. As a result, readers with Down syndrome may be more familiar with the orthographic forms of the high frequencies words we included in our sentence materials than will their reading-level-matched peers and, further, may have developed ocular-motor patterns (whether efficient or not) that inexperienced readers may not yet have (Aghababian & Nazir, 2000; McConkie et al., 1991; Rayner, 1986). Bearing this caveat in mind, based on results of adult studies, we predicted that the group of readers with Down syndrome may show shorter saccades, longer fixation times, and a greater proportion of regressive saccades than will the typically developing readers during the first-pass through a sentence, if their reading skills are less developed. In addition, we hypothesized that the Down syndrome group may spend more time re-reading overall, leading to longer total reading times than those for the typically developing group. Last, we predicted that the level of sentential complexity will have differential effects in the two groups. The Down syndrome group may show greater differences in reading measures between the syntactically complex relative clause sentences and simpler, single clause sentences than will the typically developing group.

Method

Participants

We recruited individuals from associations (groupe d'etude pour l'insertion sociale des personnes porteuses de trisomie 21 [group for the social insertion of individuals with trisomy 21, Geist 21] and specialized institutes. We selected individuals with Down syndrome on the basis of their pre-established reading ability, which ranged from first to third year elementary school level, as determined by the Test de l'Alouette. This standardized reading test essentially measures phonological decoding skills under timed conditions and was administered by a professional during the course of the participants' education (exact scores were not provided to the authors). All participants chosen had established phonological decoding skills to at least the first grade level (Classe Préparatoire in France). Because this test does not provide a measure of either semantic or syntactic processing and no standardized outside measure of reading abilities on these latter areas were available, we used a posttest to verify participants' knowledge of the vocabulary items used in the present study.

We selected 9 participants, including adolescents and young adults with Down syndrome who had full trisomy 21 as reported in their medical records. They ranged in age from 15 to 28 years (M = 20, with 5 participants aged 15 to 20). All were native French speakers, with at least one French parent. All had received scholastic instruction up to at least age 14, either in an inclusive school (4 of the 9 adolescents) or in segregated institutes.

We chose 9 typically developing children, aged 6 to 9 years, to match the same reading grade levels as those of participants in the Down syndrome group. All were native French speakers enrolled in elementary school and at grade-level for their reading abilities as reported by their primary teacher (no Test de l'Alouette scores were available for this group). Eight of these children's eye-movements were recorded. For all participants, we obtained informed written consent prior to their inclusion in the study, which was approved by the French ethics committee.

Recording

We recorded participants' eye movements in our experimental laboratory using an EyeLink II apparatus and standard software and perfomed a calibration session for each participant prior to the warm-up session and each experimental block. Although during the experiment viewing was binocular, we only recorded the right eye, with a sample rate of 500 Hz. Participants kept their chin in a chin rest, 60 cm from the screen, while reading. They were asked to read silently to avoid jeopardizing calibrations due to head movements. 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) and appeared on a single line. Brightness and contrast were held constant across all participants/sessions.

Materials and Design

Sentences were of three levels of difficulty: (a) a simple declarative structure comprised of a subject noun, lexical verb, and object noun (NVN) (e.g., La fille mange une pomme. [The girl eats an apple.]); (b) the same SVO structure but with a copula and a locative preposition (NVPP) (e.g., Le chat est derrière l'arbre. [The cat is behind the tree.]); and (c) increased syntactic complexity introduced by an apposed subject relative clause (e.g., Le garçon regarde le chat qui est debout. [The boy looks at the cat that is standing up.]). Examples 1 to 3 are provided below. Pragmatics generally did not allow for comprehension of the relative clauses, as illustrated in the example (both entities could perform the actions described by both verbs as opposed to a sentence such as The boy looks at the bird that is flying.). All words were of high printed frequency, presented in French elementary-school norms (Lété, Sprenger-Charolles, & Colé, 2004), and formed part of the participants' spoken and reading vocabulary as established by administration of a posttest. In the posttest, we asked all participants to read each word, presented independently in a printed list, out loud; no scores were tallied for this verification test; however, all participants were able to read all of the individual words. We used 18 lexical verbs in addition to the copula *to be*, 35 common nouns, and 9 prepositions.

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

We created three blocks of sentences, with nine sentences and an equal number of each sentence type (NVN, NVPP, and relative clauses) per block. A different random assignment of sentences to blocks was created for each participant; all sentences were, thus, seen across participants in all positions (beginning, middle, and end of the session). The session began with seven practice sentences comprised of two of each sentence type, using the same vocabulary as test sentences, and a personalized lead-in sentence (Hello _____ [participant], you are now going to read sentences presented on the screen). The practice sentences were representative of the experimental sentences.

Procedure

A trial began with a warning tone followed by a fixation star positioned at the left of the screen. Once the eye was detected, the star was replaced by a sentence that was shown in its entirety on a single line. Participants were required to read silently for comprehension and to press the space bar after completing the sentence. Thereafter, two line drawings were presented, on the left and right half of the screen, only one of which depicted the meaning of the sentence. The position of the correct image was counterbalanced across sentences, being on the right for half and on the left for the other half but in the same position for all participants. The sentence was presented again along with the line drawings to reduce memory load. Participants were asked to manually indicate the correct line drawing, and responses were recorded by the experimenter, who sat next to the participant throughout the session. To reduce the likelihood that correct responses were due to guessing, we recorded very hesitant (unsure) responses and switching between images as incorrect. Only a small percentage of responses fell into this category (less than 10% in both groups). The experiment began with a practice session followed by three experimental blocks of nine sentences, with a short pause between blocks. The entire experimental session including pauses lasted roughly 30 min.

Results

Comprehension Accuracy

Mean comprehension scores for each reader are shown as a function of sentence type in Table 1. We conducted a 2 (group) × 3 (sentence type) ANOVA on the mean scores per participant and found an effect of group, $F(1, 16) = 23.96$, $p < .001$, which was not significantly modified by sentence type, $F(2, 32) = 2.01$, $p < .15$. Comprehension scores were higher overall in the typically developing than in the Down syndrome group. In the typically developing group, there was ceiling level accuracy for all sentence types and little variation across participants. Comprehension among readers with Down syndrome ranged from 67% to 100% for single clause sentences and from 44% to 89% for relative clause sentences.

Reading Measures

We performed analyses on all sentences that were correctly understood, were read at least once in a complete left-to-right manner, and were recorded without loss of the eye-tracker. For a given participant, data were retained provided that at least one third of the sentences could be analyzed per condition. Given these criteria, data from 7 participants with Down syndrome and 7 typically developing children were retained for

Table 1. Mean Comprehension Scores by Individual Reader, Group, and Sentence Type

	Down syndrome			Typically developing		
Reader	NVN[a]	NVPP[b]	Relative[c]	NVN	NVPP	Relative
1	89	67	56	100	100	100
2	100	89	78	100	100	100
3	78	67	44	100	100	100
4	89	100	78	100	100	100
5	78	89	44	100	100	100
6	67	89	44	100	100	67
7	100	78	70	89	100	100
8	75	100	70	100	78	89
9	88	67	90	100	100	67

[a]Subject noun, lexical verb, and object noun. [b]Single clause: noun, verb, prepositional phrase. [c]Main clause followed by subject relative clause.

analyses for single clause sentences and from 6 participants from each group for relative clause sentences. The reading level of the 7 participants from each group remained roughly matched following selection (2 first-grade typically developing children were not retained, whereas 1 first-grade and 1 third-grade reading level participants with Down syndrome were not retained). In the Down syndrome group, the percentage of sentences analyzed per participant varied from 33% to 89% per sentence type, with a total of 62%, 65%, and 44% of sentences analyzed for NVN, NVPP, and relative clause sentences, respectively. The percentage of sentences for the typically developing group analyzed per participant varied from 33% to 100% per sentence type, with a total of 64%, 64%, and 65% of sentences analyzed for NVN, NVPP, and relative clause sentences, respectively.

We calculated mean first-pass gaze durations and total reading times as a function of sentence type and region of interest, with three regions for NVN and NVPP sentences and five regions for relative clause sentences, as shown in Examples 1, 2, and 3 (p. 197). These regions correspond to major grammatical classes. Mean length in character spaces of the first three regions was 10.4, 5.8, and 9.8 for NVN sentences; 9.4, 10.6, and 9.4 for NVPP sentences; and 9.1, 8.2, and 8.6 for relative clauses, with a mean of 9.8 and 8.8 for the fourth and fifth regions of relative clauses. For NVPP sentences, the copula and preposition were treated as a combined region to avoid loss of data due to the skipping of short regions (Rayner, 1998). For all sentences, nouns were examined as complete noun phrases (article + noun) both because the article is generally visible in the periphery when the eye fixates on the first letters of the noun and because, in French, nouns without articles are not permissible.

By examining each region independently, we were able to determine the trajectory of the participant's eyes through the sentence, both during the first reading, revealed by first-pass gaze durations, and during subsequent re-readings, revealed by total reading times and determine whether and where difficulties may have occurred. *First-pass gaze durations* were defined as the sum of all fixations within a region from the time the eye first entered the region prior to exiting to the right or left. This measure provides an indication of initial processing for each region as well as an indication of where initial difficulties may have occurred. *Total reading times* were defined as the summation of all fixations in a region. This measure provides a picture similar to the first-pass reading, but at a more macro level. It can also reveal processing that was not completed during the first reading of the sentence. We also calculated average fixation durations independent of region. This measure simply provides a comparison; it allowed us to determine whether the average performance of readers with Down syndrome was similar to the average performance of the typically developing group. Last, we computed the percentage and amplitude of forward saccades, in number of character spaces. This measure provides both a means of general comparison between the two groups as well as possible indications of linguistic processing difficulty. Although saccade durations were recorded, they were not considered further.

Saccades

The mean percentage of forward saccades during the first pass through the sentence was calculated for each group. In the Down syndrome group, forward saccades represented 60%, 65%, and 71% of saccades for NVN, NVPP, and relative clause sentences, respectively. In the typically developing group, these percentages were 70%, 72%, and 78%, respectively. The percentage of forward saccades was, thus, higher than that of regressions in both groups; however, there was substantial variation in the Down syndrome group and comparatively more so than in the typically developing group. Compared to the typically developing group, the Down syndrome group tended to make fewer forward saccades (i.e., more regressions) for single clause (NVN and NVPP) sentences, $F(1, 12) = 3.17$, $p < .10$, as well as for sentences containing a relative clause, $F(1, 10) = 6.36$, $p < .13$, although neither of these comparisons reached standard levels of significance.

We calculated the mean amplitude of forward saccades for each group as a function of sentence type and performed separate ANOVAs on the single clause sentences (NVN and NVPP) and sentences containing a relative clause with group as a between-participant factor. We found a main effect of group due to the typically developing group having greater mean saccade amplitude than did the Down syndrome group for both single clause sentences, $F(1, 12) = 4.79$, $p < .05$,

< $\eta p^2 = .29$), and sentences containing a relative clause, $F(1, 10) = 26.72$, $p < .0004$, $\eta p^2 = .73$. For NVN, NVPP, and relative clause sentences, respectively, mean amplitude of forward saccades was 4.2, 4.4, and 3.5 character spaces in the Down syndrome group and 5.7, 5.6, and 5.9 character spaces in the typically developing group. Independent ANOVAs in both groups revealed that saccade amplitude did not differ as a function of sentence type in either the Down syndrome group or the typically developing group.

Average Fixation Durations

We calculated the average fixation durations for each group for each sentence type and performed separate ANOVAs on the single clause sentences (NVN and NVPP) and sentences containing a relative clause, with group as a between-participant factor. No main effects or interactions were found. In the Down syndrome group, mean fixation durations were 277, 281, and 270 ms for NVN, NVPP, and relative clause sentences, respectively. In the typically developing group, mean fixation durations were 286, 282, and 282 ms for NVN, NVPP, and relative clause sentences, respectively.

First-Pass and Total Reading Times

Mean first-pass and total reading times are reported as a function of region and sentence type for each participant group in Table 2. We performed ANOVAs on the means for each sentence type independently and applied the Greenhouse-Geisser (1959) correction to all repeated measures with greater than one degree of freedom. All significant differences involving more than two conditions were confirmed by post-hoc comparisons.

For NVN sentences, a 2 (group) × 3 (region) ANOVA performed on mean first-pass gaze durations revealed effects of group, $F(1, 12) = 7.17$, $p < .02$, $\eta p^2 = .37$, and region, $F(2, 24) = 33.89$, $p < .001$, $\eta p^2 = .74$, with no interaction effect. Mean reading times were significantly longer in the Down syndrome than in the typically developing group (858 vs. 581 ms, respectively). Post hoc comparisons of sentence regions (Tukey HSD) revealed longer gaze durations for the final region (915 ms) compared to the first (737 ms), $p < .005$, and second region (506 ms), $p < .001$. The same analysis of total reading times revealed a similar pattern, with a significant effect of group, $F(1, 12) = 5.13$, $p <$

Table 2. First-Pass Gaze Duration and Total Reading Times by Group

	Readers with Down syndrome				Typically developing readers			
	Gaze		Total		Gaze		Total	
Sentence	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
NVN								
NP1	885	252	1495	321	589	129	1006	79
Verb	607	239	1255	330	406	237	738	433
NP2	1083	237	2097	827	747	212	1674	649
NVPP								
NP1	918	359	1554	430	586	270	932	305
Copula + preposition	1135	470	2025	626	558	180	1076	302
NP2	1223	713	2629	1172	850	198	1265	242
Relative clause								
NP1	755	290	1227	868	552	86	780	141
Verb	935	558	1459	884	436	59	708	201
NP2	767	415	1335	634	389	90	762	141
Rel	1234	477	2185	662	456	134	808	146
End	909	337	2308	1303	756	268	1218	395

Note. Mean first pass gaze durations and total reading times for correctly interpreted sentences as a function of sentence type, sentence region (NVN = single clause: noun, verb, noun; NVPP = single clause: noun, verb, prepositional phrase, Relative = main clause followed by subject relative clause) and participant group. NP1 = first noun phrase in sentence. NP2 = second noun phrase in sentence.

.04, $\eta p^2 = .30$, and region, $F(2, 24) = 20.30$, $p < .0001$, $\eta p^2 = .63$, with no interaction effect. Total reading times were longer in the Down syndrome than in the typically developing group (1616 vs. 1139 ms, respectively). Post hoc comparisons (Tukey HSD) revealed longer reading times for the final region (1886 ms) compared to the first (1250 ms), $p < .01$, or second (966 ms) region, $p < .001$, which did not differ significantly from each other.

For NVPP sentences, we performed a 2 (group) × 3 (region) ANOVA on mean first-pass gaze durations that revealed effects of group, $F(1, 12) = 5.22$, $p < .05$, $\eta p^2 = .30$, and sentence region, $F(2, 24) = 4.41$, $p < .03$, $\eta p^2 = .27$, with no interaction effect. Reading times were longer in the Down syndrome than in the typically developing group (1092 vs. 665 ms, respectively). Post-hoc comparisons (Newman-Keuls) revealed that the effect of sentence region was due to longer reading times in the final region (1034 ms) than initial region (751 ms), $p < .02$, with a trend for a difference between the final and second region (847 ms), $p < .06$. The same analysis of total reading times revealed a similar pattern, with significant effects of group, $F(1,12) = 16.11$, $p < .005$, $\eta p^2 = .57$, and sentence region, $F(2, 24) = 7.40$, $p < .01$, $\eta p^2 = .38$, and no interaction effect. Total reading times were longer in the Down syndrome than typically developing group (2068 vs. 1091 ms, respectively). Post-hoc comparisons (Neman-Keuls) of the sentence regions confirmed longer processing time in the final region (1947 ms) compared to the first (1241 ms), $p < .01$, or second region (1550 ms), $p < .05$, and a small trend for a difference between the first and second region, $p < .10$.

For relative clause sentences, the analysis of eye movements was undertaken, although caution is warranted given that only 44% of sentences could be analyzed in the Down syndrome group versus 65% in the typically developing group. As reported above, only sentences that were correctly understood were analyzed.

We performed a 2 (group) × 5 (region) ANOVA on first-pass gaze durations and revealed an effect of group, $F(1, 10) = 8.55$, $p < .02$, $\eta p^2 = .46$, a trend for the effect of sentence region, $F(4, 40) = 2.89$, $p < .065$, $\eta p^2 = .22$, and a significant interaction effect, $F(4, 40) = 3.37$, $p < .04$, $\eta p^2 = .25$. We conducted independent analyses on the data for each reader group. In the Down syndrome group, there was a trend for the effect of sentence region, $F(4, 20) = 2.40$, $p < .08$, $\eta p^2 = .32$. Post-hoc comparisons (Newman-Keuls) revealed that mean gaze durations tended to be longer for the fourth region (1234 ms), which contained the relative pronoun and subordinate verb than for each of the prior three regions, namely, the first noun (755 ms), $p < .09$, main verb (935 ms), $p < .07$, and the second noun (765 ms), $p < .10$, which was both the object of the main verb and the head of the relative clause. In the typically developing group, there was an effect of sentence region, $F(4, 20) = 6.63$, $p < .02$, $\eta p^2 = .57$. Post-hoc comparisons (Newman-Keuls) revealed that mean gaze durations were longer in the final region (756 ms) compared to each of the first four regions (first noun 552 ms, $p < .02$; main verb 436 ms, $p < .004$; second noun 389 ms, $p < .002$; relative pronoun + subordinate verb 456 ms, $p < .004$, which did not differ from each other.

We performed a 2 (group) × 5 (region) ANOVA on total reading times, which revealed effects of group, $F(1, 10) = 7.72$, $p < .02$, $\eta p^2 = .44$, and of sentence region, $F(4, 40) = 6.26$, $p < .02$, $\eta p^2 = .38$, with no interaction effect. Post hoc comparisons (Tukey HSD) revealed longer mean durations for the fourth and fifth (final) regions (1496 ms and 1763 ms, respectively) compared to the first three sentence regions (1004, 1084, and 1048 ms for the first, second, and third region, respectively, $p < .001$ to $p < .005$. Neither the last two regions nor the first three differed significantly from each other.

Discussion

The results of the present pilot study provide interesting and novel information in relation to the processes used by individuals with Down syndrome 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, to our knowledge.

As a general caveat, we note the substantial interindividual variation in performance, as is often the case in this population (Boudreau, 2002; Rondal, 1995). Nonetheless, we did find general trends. Comprehension was higher for syntactically simple sentences (NVN and NVPP) than for sentences containing a main clause and subject relative clauses as could be expected. Over half of the readers with Down syndrome showed relatively good comprehension of subject relative clauses; however, as revealed by their offline scores showing 70% comprehension and above for 5 of the 9 participants, which suggests that at least a percentage of readers with Down syndrome surpassed a rudimentary level of syntactic comprehension (Groen et al., 2006; Rondal, 1995; Thordardottir et al., 2002), although further work with a larger sample is, of course, warranted to substantiate this finding. 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.

Consider first the most general measures of reading, which are the mean duration of a fixation, the ratio of forward saccades to regressions and the amplitude of saccades. Our results revealed, interestingly, that mean fixation durations did not differ appreciably between the typically developing and Down syndrome group. Moreover, both groups showed fairly homogeneous results on this measure. The mean duration of fixations was, furthermore, in line with what has been reported for beginning readers (Rayner, 1986). For saccades, a rather different picture emerged. On average, the readers with Down syndrome showed 65% of forward saccades across all sentence types, somewhat lower than readers with typical development who were at the same reading level. On average, they made 73% of forward saccades, consistent with findings for second grade readers (Rayner, 1986). In addition, there was a large degree of variability in the Down syndrome group, with 3 of the 7 participants recorded showing an almost equal ratio of regressions to forward saccades, which was not the case in the typically developing group, where only 1 participant, in fact, the youngest and least experienced reader, showed such. Note, however, that the statistical comparison of the two groups showed only trends for a difference between them; therefore, caution is warranted before making any definitive conclusions. In addition, these results would be bolstered by additional studies with a larger sample size.

The mean amplitude of saccades in the Down syndrome group was roughly 4.5 character spaces for single clause sentences and 3.5 character spaces for sentences containing a relative clause. Although small in amplitude, these values are not far below the performance reported for typically developing children at second-grade reading level (Rayner, 1986) and, although significantly shorter, were not far below the results we obtained in the typically developing group. Rayner has suggested, as have other researchers (Fisher, 1979; Taylor, 1965, cited in Rayner, 1986) that beginning (second grade level) readers have smaller perceptual spans and focus their attention on the foveal region, which may partially account for shorter saccades in young readers (for a discussion of literacy development, see Ashby & Rayner, 2005). Taken together, the shorter saccade length and slightly greater proportion of regressive saccades in the group of readers with Down syndrome compared to our group of typically developing readers nonetheless suggests an overall greater level of difficulty in sentence processing in the former group.

In addition to the general measures outlined above, our results also provide more specific information about reading comprehension, as revealed by the pattern of reading times across the different regions of sentences. For the single clause declarative sentences, the pattern of results obtained for readers with Down syndrome was qualitatively the same as that obtained for typically developing readers. In both groups, we found elevated reading times at the last region of the sentence. This effect, known as the *sentence wrap-up effect* is generally attributed to readers taking time at the final region of the sentence to consolidate information and, if necessary, perform reanalysis (Just & Carpenter, 1980; Mitchell & Greene, 1978; Rayner, Kambe, & Duffy, 2000). For single clause sentences, we found this pattern in both the first-pass through the sentence and in the total reading times. 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 even in typical reading, they reread it. The high level of comprehension for these sentences also supports this conclusion. It is quite interesting that the only reliable difference between the results obtained for readers with Down syndrome and those developing typically was a general increase in reading times in the latter group, which was roughly twice as long for all regions. The pattern of reading times was, however, the same for the two groups, and this was true for both the first reading of the sentences as well as for subsequent re-readings.

For sentences with a higher level of complexity (i.e., those containing a main clause followed by a subject relative clause), the pattern of reading times from the beginning to the end of the sentence revealed differences between the two groups of readers. The pattern observed in the typically developing group was increased reading times at sentence end from the first reading, which suggests that these participants understood both the main clause and relative clause the first time they read the sentence and, accordingly, took time to "wrap-up" comprehension at sentence end. Such was not apparent for readers in the Down syndrome group. They increased reading times during the first reading of the sentence at the point where the main clause ended (i.e., at the relative clause). Only during re-readings of the sentence did we observe longer reading times for this group (i.e., sentence wrap-up effects at the final region of the relative clause sentences). In other words, although both groups showed comprehension of apposed subject relative clauses, the typically developing group demonstrated this from the first reading, whereas the Down syndrome group apparently engaged in a two-step process. These readers understood the main clause during the first reading of the sentence and the relative clause, during subsequent re-readings of the sentence.

In comparison to previous studies of typically developing readers and in comparison to the data we obtained in the present study, our results for the readers with Down syndrome are encouraging. At a general level of processing, they apparently experienced somewhat more difficulty than reading-level-matched typically developing children. Their proportion of forward to regressive saccades and the relatively small size of forward saccade amplitude suggest a "choppier," more hesitant reading strategy than what we observed for the typically developing group and what has been reported in previous studies with young typically developing readers (McConkie et al., 1991; Rayner, 1986). Despite this hesitancy, the pattern of first-pass and total reading times suggest quantitative rather than qualitative differences between readers with Down syndrome and our group of beginning readers, at least with regard to the processing of single clause declarative sentences. For syntactically more complex sentences, the readers with Down syndrome showed delayed effects compared to the typically developing readers. Their pattern of eye-movements suggests comprehension of the relative clause only during re-readings as opposed to during the first reading of sentences, although the relatively low proportion of sentences that could be analyzed for the eye-movement in the Down syndrome group precludes strong conclusions. Last, we note that the present study was conducted with individuals who have Down syndrome and were literate and able to phonologically recode, such that any generalizations are limited to individuals with similar capacities. Our study, nonetheless, provides a promising first glimpse at how individuals with Down syndrome read online.

There are two caveats for our results in the present study. The first is related to the comparison of the group of readers with Down syndrome to the typically developing readers. These groups were grossly matched on reading ability, based on a standardized test of phonological decoding for the Down syndrome group versus teacher report for the typically developing group. The two groups were not matched on either verbal or nonverbal MA nor on other measures of syntactic processing. As such, the comparison of the two groups is rough, at best. The second limitation is linked to the possibility that the readers with Down syndrome, in comparison with those in the typically developing group, may have had added difficulty in reading due to poor ocular-motor control. Over 80% of children with Down syndrome have ophthalmological disorders (Roizen & Patterson, 2003) and among the most frequent of these are two that have an immediate impact on the ocular-motor control necessary for effective reading (strabismus [40%] and nystagmus [20%]). Despite this lack in ocular-motor control for syntactically simple, subject–verb–object sentences, the Down syndrome group did not, in fact, differ from the typically developing group in the overall pattern of eye-movements. As such, it seems safe to conclude that differences between the two groups for the syntactically complex sentences was due at least as much to differences in comprehension as to ocular-motor control.

Conclusions

Although preliminary given the small sample studied, the results we obtained are promising and warrant future studies of eye movements as a measure of reading comprehension in readers with Down syndrome. The measures we investigated (proportion and amplitude of forward saccades, mean fixation durations, first-pass, and total reading times) provide a window into how these readers process sentences online and information that, to our knowledge, has not been previously reported for this population. Further research with a larger sample and more specific research hypotheses is, of course, necessary to substantiate the findings reported here.

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