

# An Exploratory Study of Reading Mathematical Expressions by Braille Readers

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## Abstract

*Introduction:* Braille readers encounter difficulties when reading mathematical expressions. In this exploratory study, we created a setting to investigate these difficulties. *Method:* Using a motion-capturing system, we analyzed the tactile strategies of three braille readers while they read mathematical expressions. To compare tactile with visual reading strategies, we also analyzed the oculomotor performance in five print readers. *Results:* The analysis showed that the two experienced braille readers needed about 3.5 times as much time as print readers to read and solve four items involving mathematical expressions. The braille readers used personal reading strategies for all items with little use of the structure of the expression. In contrast, the reading strategies of print readers showed item-dependent and structure-related characteristics. *Discussion:* The braille readers had difficulties, within the constraints of tactile reading, to align their reading strategies with the solution procedures required by the mathematical structure of the items. *Implications for practitioners:* Teachers need to become aware of the kind of problems that braille readers confront when they try to comprehend and solve mathematical problems.

*Keywords:* braille reader, eye tracking, finger tracking, mathematical expression, reading strategy

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## **An Exploratory Study of Reading Mathematical Expressions by Braille Readers**

Mathematics education is important for professional careers and further study in today's technology-rich society. To access and work with mathematical objects, students need to communicate and manipulate representations such as formulas, graphs, and tables (Duval, 2006). Sighted students have the ability to have an instantaneous overview over a mathematical expression. Back and forth scanning with the eyes allows them to identify the bracketed parts. Students who are visually impaired and use braille as their primary literacy medium (hereafter referred to as braille readers) easily lose track when interacting with these representations in braille, in synthetic speech, or in tactile diagrams. This difficulty with serial processing in braille readers maybe one reason why they do not have equal opportunities to sighted students (hereafter referred to as print readers) to fulfil their potential in mathematics (e.g., Fajardo-Flores & Archambault, 2012, 2014). To provide better support for these students, we investigated the performances and strategies of braille readers in mathematics using finger-tracking technology. Since little is known about the visually guided strategies of print readers when they are confronted with mathematical expressions, we also performed a study using eye tracking in print readers (Schneider, Maruyama, Dehaene, & Sigman, 2012). We expected that visual reading strategies have the potential to provide clues to support braille readers in trying to read and comprehend mathematics.

### **Theory on Tactile and Visual Reading Strategies**

#### **Tactile Reading Strategies**

The tactile reading strategies of braille readers can be studied through finger-tracking technology (Breidegard, 2007; Breidegard, Jönsson, Fellenius, & Strömqvist, 2006; Breidegard et al., 2008; Hughes, McClelland, & Henare, 2014; Perea, Jiménez, Martín-Suèsta, & Gómez, 2015). The tactile perceptual window, approximately equal to one finger pad, is much smaller than the visual perceptual window (Loomis, Klatzky, & Lederman, 1991). To identify a word, one needs to perceive each character and integrates this character with previously stored information (Dimitrova- Radojichikj, 2015). It has been shown that tactile reading of nonmathematical text is about 3 times slower than visual reading (Mohammed & Omar, 2011; Perea et al., 2015).

Bertelson, Mousty, and D'Alimonte (1985) observed two types of finger cooperation in braille reading on paper: conjoint and disjoint. In conjoint reading, the fingertips of the two index fingers are about one or two braille cells apart, often touching each other. In disjoint reading, the two index fingers explore different parts of the line. According to Breidegard,

Jönsson, Fellenius, and Strömquist (2006), conjoint reading is most appropriate for efficient and deep reading and disjoint reading for global scanning of text. Perea, Jiménez, Martín-Suesta, and Gómez (2015) used the term *linger* when the reading finger is slowing down and lingering on one braille cell. Braille readers only read in the left-to-right direction. Displacements of the finger over the braille display in the right-to-left direction are tactile regressions. These regressions are less intentional as visual regressions because a preview of the braille cell or cells one plans to go to is not available (Perea et al., 2015). In this study, tactile scan paths are the successive positions of each index finger on the braille display while reading a text.

Mathematical text is compact, context poor, and contains more symbols than non-mathematical text. Therefore, precise reading is critical, which could be difficult for braille readers because characters in braille have a low level of redundancy (Tobin & Hill, 2015). Furthermore, to comprehend the structure of an expression, braille readers have to sequentially build an overview over the expression. Consequently, they may be hindered by limitations in working memory or in the process of integrating the tactile information (Loomis et al., 1991).

### **Visual Reading Strategies**

In general, visual reading strategies are based on oculomotor performance assessed with an eye-tracking system. While reading, a sighted person perceives information during a fixation, a period of about 200-300 microseconds, during which the eyes remain focused on one position (Rayner, 1998). During this period, the perceptual window consists of a foveal area surrounded by a near foveal area. In terms of reading text, the foveal area is about 6-8 characters, the near foveal area extends to 14 characters (Engbert, Longtin, & Kliegl, 2002). People can only differentiate characters in a word in the foveal and near foveal area (Traxler, 2012). To go from one fixation to another, a person generates a saccade, a rapid eye movement, that lasts between 30 and 80 microseconds. It has been proposed that information extracted from the near foveal is used to direct a forward or backward saccade (regression) toward the following fixation point (Juhász, White, Liversedge, & Rayner, 2008; Schneider, Maruyama, Dehaene, & Sigman, 2012). The position of fixations and the sequence of fixations, saccades, and regressions can be described in a visual scan path (Noton & Stark, 1971).

## Methods for Exploring Reading Strategies

In their eye-tracking study, Schneider, Maruyama, Dehaene, and Sigman (2012) investigated reading strategies of print readers. More than 30 participants calculated several expressions: for example,  $4 + (3 \times 2 - 5)$  and  $4 + [1 - (3 + 2)]$ . The authors found that the spatial sequences of the eye movements, reflected by the visual scan paths, correspond with the expected sequences based on the syntactic structure of the expression. Although brackets do not receive frequent or long fixations, they appear to have a strong influence on how sighted participants parse mathematical expressions (Schneider et al., 2012).

In the study of Fajardo-Flores and Archambault (2012), participants who were blind and sighted participants solved four algebraic expressions orally. Participants were not allowed to take notes and had to rely on their memory and the help of the observer. The results showed that, without the constraints of tactile reading, the intentions of all participants were related to the structure of algebraic procedures.

Perea and his colleagues (2015) examined how letter position was identified in reading sentences that either were intact or involved letter transpositions. They conducted two parallel studies, one with braille readers using finger tracking and the other with print readers using eye tracking. Measurements of reading difficulties were number of words per minute, number of lingers and fixations, and percentage of tactile and visual regressions. Their method led to insights that contribute to the knowledge of processing transposed letter words in general.

In the current study, which has some similarities to the approaches just described, we examined the strategies of braille and print readers to investigate the strategies of braille readers while reading mathematical expressions on a braille display.

### Research Questions and Hypotheses

The aim of the study is 2-fold. First, to gain insight into the strategies of braille readers while reading mathematical expressions. Second, to better understand possibilities and limitations of reading mathematics in braille by comparing tactile with visual scan paths. These aims are divided into two research questions:

Research question 1 : *How do braille and print readers perform on reading and solving mathematical expressions?*

Hypothesis 1: Based on studies on tactile perception of pictures (Foomis et al.,

1991) and of nonmathematical text (Mohammed & Omar, 2011; Perea et al., 2015; Tobin & Hill, 2015), we expect that in our study, braille readers make more reading errors and need more time.

Research question 2: *Which tactile and visual strategies do braille and print readers, respectively, use while reading mathematical expressions?*

Hypothesis 2: Braille readers are expected to read the expression from left to right starting at the first braille cell. They have to sequentially build an overview and will therefore have to reread (parts of) the expression more often. Ineffective tactile regressions will augment the amount of rereading further in the process, which will result in (relative) long tactile scan paths. We conjecture that the sequence of the eye movements of print readers corresponds with the expected sequences based on the syntactic structure of the expression (Fajardo-Flores & Archambault, 2012; Schneider et al., 2012). As a result, eye movements will produce (relative) short visual scan paths. Finally, we expect that print readers use brackets for parsing the expressions but do not explicitly fixate on them (Schneider et al., 2012).

## Method

### Design of the Study

To investigate the research questions in this exploratory study, two settings were created, one using a finger-tracking system to analyze tactile reading strategies and the other using an eye-tracking system to analyze visual reading strategies. The students were asked to read and solve four items involving mathematical expressions. All students were offered the same items in an identical order.

The braille readers read the expressions on a braille display without the support of synthetic speech.

### Participants

Due to the limited number of braille readers in secondary education, approximately 80 in the Netherlands, we selected 3 students who mastered mathematics at the ninth-grade level. Sylvia (pseudonym) was in 9th grade, and Joris (pseudonym) was a 10th-grade student. Michael (pseudonym) was an undergraduate university student. Sylvia and Michael developed blindness at a very young age and started reading braille at the age of 6 years. Joris was sighted and became blind, due to a disease, at the age of 12 years. Soon after, he started to learn braille. All three braille readers had no comorbidities. Sylvia and Joris attended a special secondary school for students with visual impairments. Before the actual test, we

checked their reading ability of nonmathematical text on the braille display. For the finger-tracking study, the students visited the Department of Neuroscience, Erasmus Medical Centre, Rotterdam.

For the eye-tracking study, six 10th-grade print readers were recruited from a suburban Dutch secondary school. The mathematics teacher, who was acquainted with the first author, selected the students. The students had typical vision. One of the students was excluded because the eye-tracking data were too inaccurate due to a poor fit of the eye-tracking eyeglasses.

Michael had already passed the national mathematics examination. All other students were still being prepared for the same examination. According to their teachers, Sylvia and Joris were “above average” level and all print readers were at “average” level. We expected all students to have acquired the mathematical abilities needed for reading and solving the selected items.

### **Items**

The students were asked to read four expressions:  $(3 \times 2 - 5) + 4$ ,  $4 + (3 \times 2 - 5)$ ,  $4 + [1 - (3 + 2)]$ , and  $[3 - (2 + 1)] + 4$ . These items were retrieved from an eye-tracking study by Schneider et al. (2012). We selected these items because the sequence of the order of required operations is not linear, except for the first item, and therefore, students had to make regressions while reading the expression.

For the braille readers, the items were typed in a Word document using the Dutch pre-braille notation, which is how braille readers in the Netherlands typically access mathematical expressions. The first author, an expert in this field, provided the translation. The first element of each expression was represented on the first, the most left, braille cell on the braille display. For the print readers, the items were created with an equation editor and resized to allow them fit on one line centered on the screen.

### **The Settings for Finger Tracking and Eye Tracking**

The finger movement patterns were recorded using a combination of a laptop computer with braille display, an infrared motion-capturing system (Vicon, Oxford, United Kingdom) and a video camera. The movements of each index finger and hand that were made within a predefined area in front of a laptop were recorded. A marker of reflective tape was attached on the nail of each index finger. The student wore a fingerless glove on each hand, on which three markers were attached, to assess global hand positions. The infrared cameras detected the position of each marker separately at a sample rate of 200 hertz. The calibration

of the cameras was done prior to each measurement series following the standardized calibration procedure prescribed by Vicon. Nexus 1.8.2 software was used to record and analyze the trajectories of each marker separately and to create an animation of the tracking in space. The x-position of the first and the last braille cell were detected to calibrate the braille display. A video camera recorded the whole session.

The eye movement patterns were recorded using a wearable eye-tracking device (Tobii glasses 2, Tobii Technology, Sweden) in combination with a laptop computer. The eye tracker had a built-in video camera; the software was able to plot the gaze points in the recorded video images simultaneously. The items were displayed on the screen of a laptop because the one-point calibration works best when presented perpendicular to the viewing direction. Every slide in PowerPoint was followed by an empty slide or a slide with a dot on it. The dot was used as an in-between calibration point. A video camera recorded overall performances.

### **Procedure**

Before the start of the experiment, all students were given oral instruction on what to expect and were motivated to do their best. Prior to each measurement, the setup used was calibrated. The students were asked to “think aloud” when reading and solving the expression. The investigator (the first author) started by saying, “Calculate the next expression.” Then the student read the expression and answered orally. At the end of the experiment, all students received a gift voucher to thank them for taking part.

### **Data Collection and Analysis**

For investigating the first research question, data were collected through audio and video recordings. We were not able to separate the reading (including comprehending) from processing because part of comprehending takes place during the processing phase. Therefore, we followed the students from the start of the reading until finding an answer to the task (reading, comprehending, and processing). Data were collected on whether the students could read and process the expression correctly and how much time they needed. The time needed per item for each braille reader and the average time for each group of students were calculated.

To answer the second research question, data were collected from the finger- and eye-tracking systems. The finger-tracking system was used to record positions of both index fingers. Horizontal finger positions were compared with the spatial location of braille cells that represent separate elements in the expressions. The eye-tracking system allowed

recording gaze positions. Horizontal fixation positions and their durations were collected for the symbols in each expression.

The ratios between the length of the scan path and the length of the expression were calculated as measurements for rereading. For the tactile scan paths, only the movements from left-to-right were taken into account. Tactile and visual time charts, representing the relative amount of time that a student focused on a particular element of the expression, were made to identify tactile, respectively, visual cues and different strategies.

## Results

For each braille reader, the amount of time needed to read and process the expression is presented (see Table 1). Sylvia needed 110 seconds, Michael 113 seconds, and Joris 292 seconds to read all items.

Table 1

*Reading and processing time (s.) per item*

Item	1	2	3	4
	$(3 * 2 - 5) + 4$	$4 + (3 * 2 - 5)$	$4 + [1 - (3 + 2)]$	$[3 - (2 + 1)] + 4$
Sylvia	34	18	35	23
Michael	29	21	36	27
Joris	109	52	85	46

For each item and for each condition, the average amount of time used to read the expression was calculated (see Table 2). For Item 1, for example, the average time needed by braille readers was 57 seconds (SD = 36.6 seconds); print readers needed 8 seconds (SD = 1.6 seconds). The braille readers needed on average 171 seconds to read all items, and the print readers needed on average 32 seconds.

Almost all students read and solved the 4 items correctly. Joris made a reading error and one print reader, Dennis (pseudonym), made an error while processing an item. The results on Item 3 provided interesting tactile and visual scan paths illustrating the relation

between what the students thought and what they did. Figures 1 and 2 represent the tactile scan paths of Sylvia, Michael, and Joris and the visual scan path of Dennis on this item.

Table 2

*Average reading and processing time (s.) per item and in total*

Item	1	2	3	4	
	$(3 * 2 - 5) + 4$	$4 + (3 * 2 - 5)$	$4 + [1 - (3 + 2)]$	$[3 - (2 + 1)] + 4$	
	M (SD)	M (SD)	M (SD)	M (SD)	Sum of Means
Visual	8 (1.6)	6 (1.1)	11 (3.1)	7 (1.4)	32
Tactile	57 (36.6)	30 (15.4)	52 (23.3)	32 (10.0)	171

In Figure 1, the tactile scan path of Sylvia is plotted in the top left panel. It illustrates how she used the second open bracket to start or end a finger movement. She started with a fast movement, from left to right, over the expression on the braille display. In the first 10 seconds, she read the expression in overlapping parts. In the next 24 seconds, she made two regressions to the first braille cell with her left index finger. Between 24 and 28 seconds, Sylvia ignored the bracket before the number 1 and checked whether it was allowed. While she uttered  $4 + 1$ , her left index finger moved to the left. During this period, her right index finger lingered on the braille cell at the end of the expression. Even after calculating  $3 + 2$ , she frequently moved with her index fingers over the right part of the expression. Sylvia started with a conjoint and ended with a disjoint reading strategy. She solved the expression in 35 seconds with a tactile scan path of about 13 times the length of the expression.

Figure 1 shows the tactile scan path of Michael in the top right panel. He started with reading the whole expression aloud, moving his index fingers from left to right. Then he calculated, after about 10 seconds,  $3 + 2$ . In the first part of the solving process, his left index finger frequently lingered on the second open bracket and in the second part on the first open bracket. He also started with a conjoint and finished with a disjoint reading strategy. He

solved the problem correctly in about 36 seconds with a tactile scan path of about 11 times the expression.

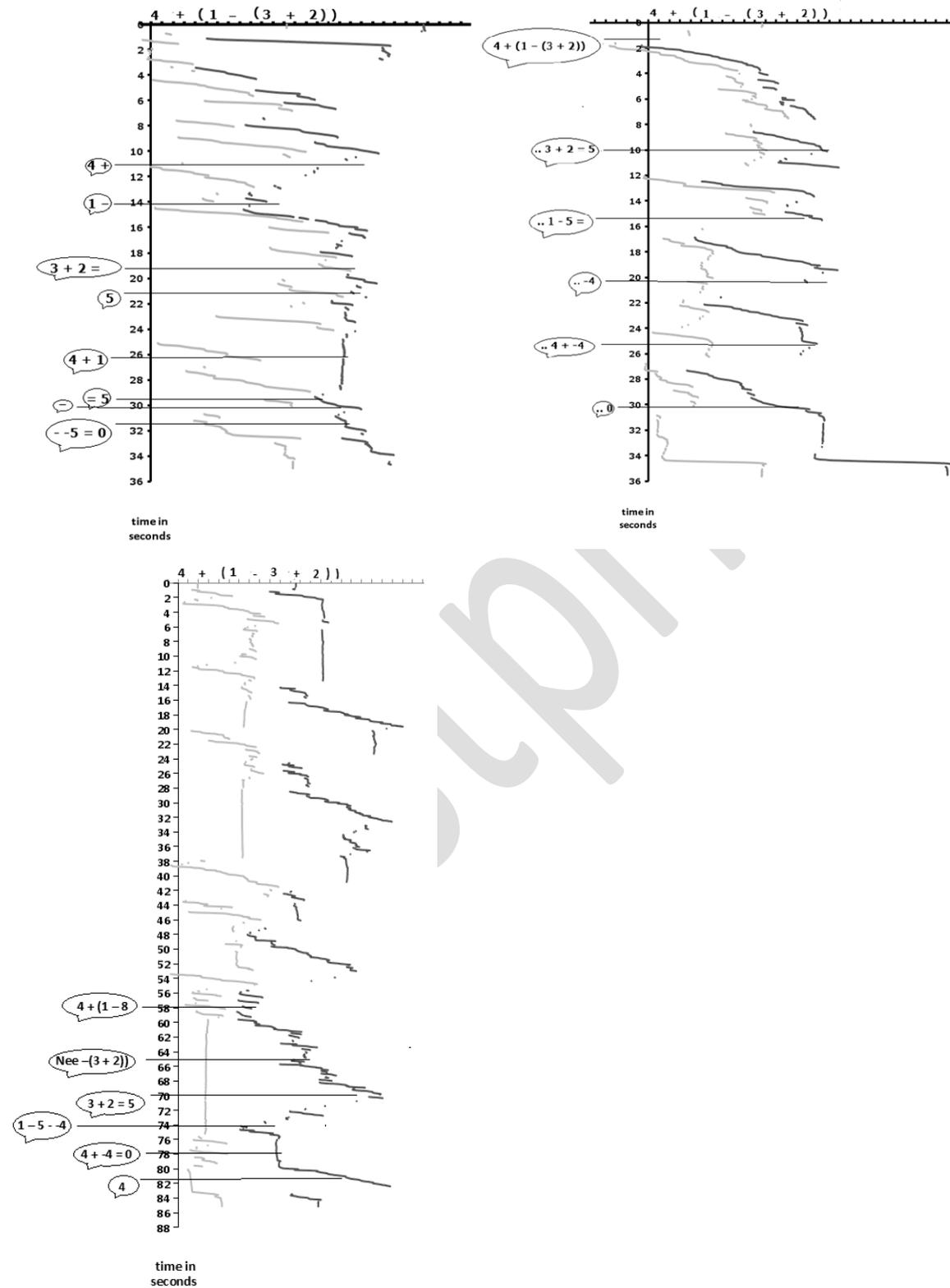


Figure 1 The tactile scan paths of Sylvia (top left), of Michael (top right) and Joris (bottom). Light grey indicates the left, dark grey the right index finger.

The tactile scan path of Joris is shown in the lower left panel of Figure 1. He frequently lingered with one or two fingers on a braille cell (on braille cells). Just after 58 seconds, he uttered  $4 + (1 - 8)$ . He made an error and corrected himself. The scan path of Joris showed a disjoint reading strategy. He solved the problem in about 85 seconds with a tactile scan path of almost 14 times the expression.

The tactile scan graphs of the braille readers were very different. Sylvia often made quite long, almost contiguous movements, from left to right over the braille cells representing the expression. Michael used his left index finger to linger on the open brackets. They both started with a more conjoint and ended with a more disjoint reading strategy. The scanpath of Joris looked very different. He lingered much more than the other braille readers, and this lingering seemed not to be controlled by the algebraic structure of the expression. He used a more disjoint reading strategy during the whole process.

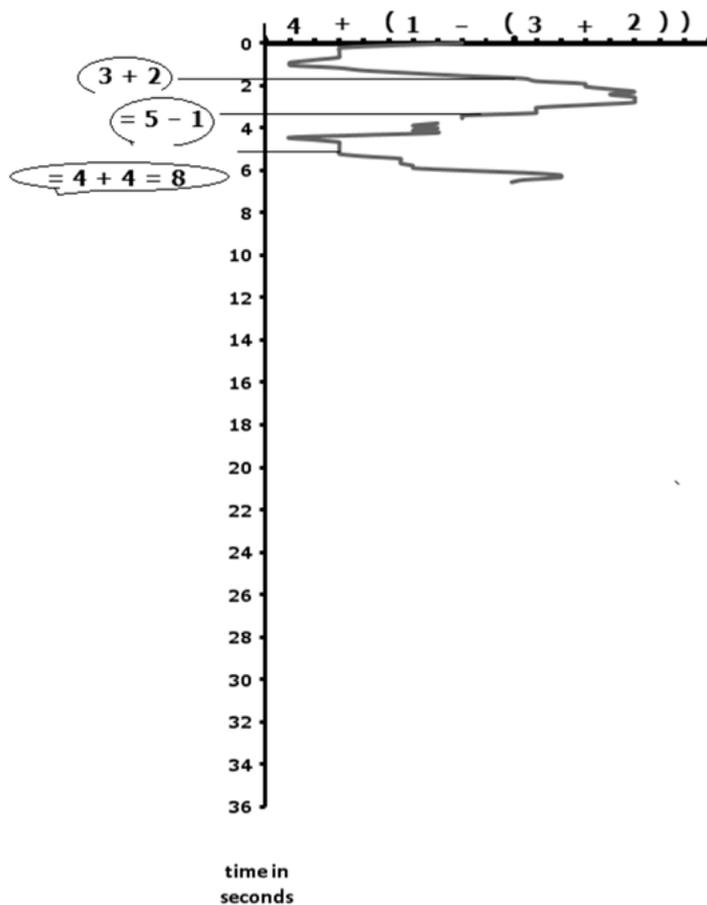


Figure 2 Dennis' visual scan path

Figure 2 shows the visual scan path of Dennis. He started to make utterances after 1.75 seconds. He did not fixate on the closed brackets. He used both pairs of brackets to



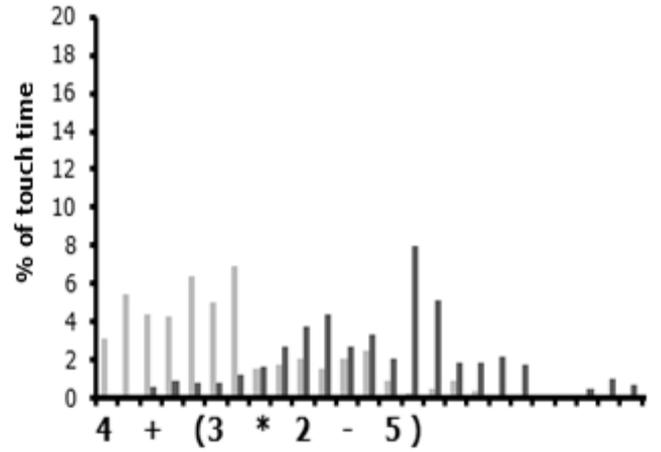
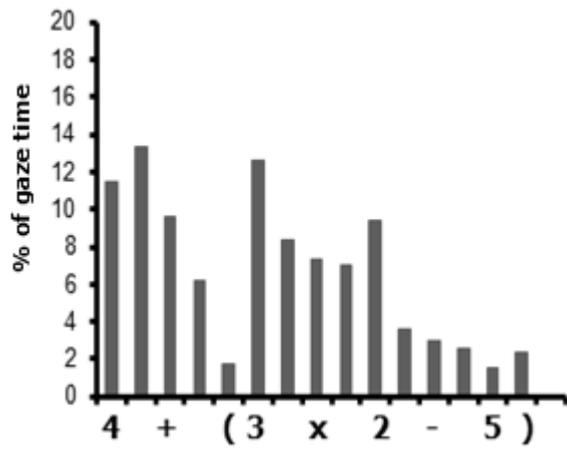


Figure 3b Visual and touch time charts for item 2

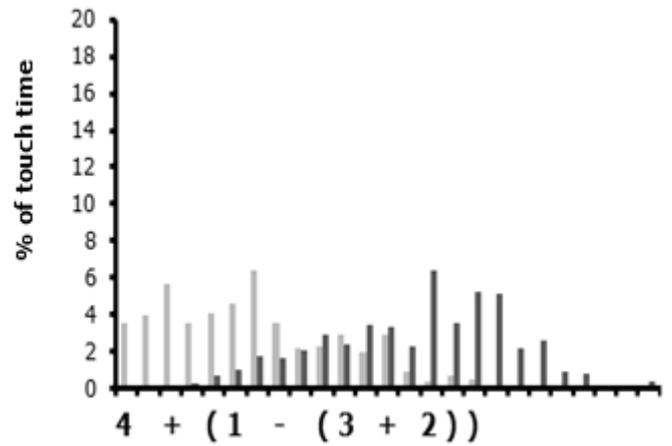
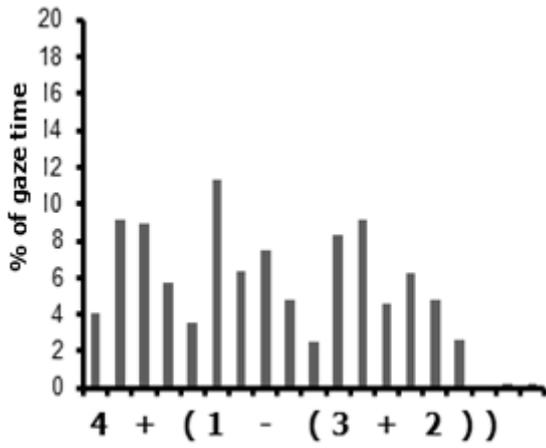


Figure 3c Visual and touch time charts for item 3

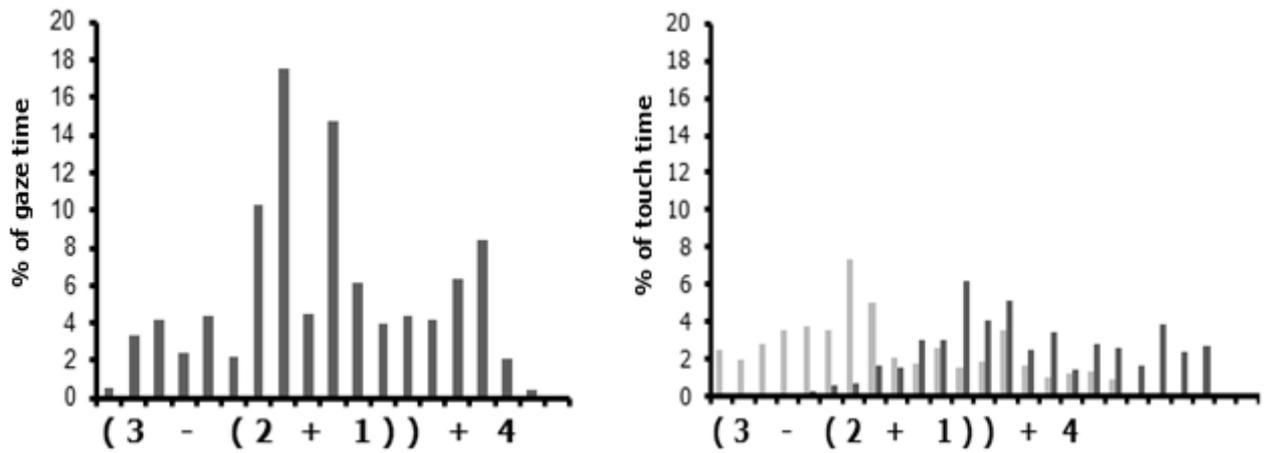


Figure 3d Visual and touch time charts for item 4

Figure 3. Visual and touch time charts, (a) Visual and touch time charts for Item I, (b) visual and touch time charts for Item 2, (c) visual and touch time charts for Item 3, and (d) visual and touch time charts for Item 4. In the touch time charts, light grey indicates the left index finger, dark grey the right index finger. In the left time chart in Figure 3a, the element “2,” for example, has a value of 12%, meaning that, on average, 12% of the gaze time of the print readers while reading and solving the first item was spent on the element “2.” In the right chart in Figure 3a, the element “” has two values: 5.1% for the left index finger and 2.6% for the right index finger, so 7.7% of all the touch time while reading and comprehending Item I goes to .” The touch time charts (in the right column) show that for all items, the left index finger is the most active finger at the left of Cell 7, the right index finger at the right of Cell 9.

Another way to analyze tactile and visual reading strategies is to compute the ratio between the length of the scan path and the length of the expression as a measure for rereading (Tables 3 and 4). The length of the tactile scan path is the total length covered by both index fingers while moving to the right. For each item, the ratio for each braille reader was calculated (Table 3). Furthermore, for each item and for each group of students, the ratio of average scan path length and expression length was calculated (Table 4). For the first item, the ratio was 13.2 (1,288.743/97.5; SD = 2.41) for the braille readers and 3.3 (416.75/125; SD = 1.41) for the print readers.

Table 3

*Ratio of tactile scan path length and expression length*

Item	1 $(3 * 2 - 5) + 4$	2 $4 + (3 * 2 - 5)$	3 $4 + [1 - (3 + 2)]$	4 $[3 - (2 + 1)] + 4$
Sylvia	13.0	9.3	12.9	9.8
Michael	10.4	7.9	11.1	9.9
Joris	16.3	8.9	13.6	6.6

Table 4

*Ratio of average scan path length and expression length*

Item	1 $(3 * 2 - 5) + 4$	2 $4 + (3 * 2 - 5)$	3 $4 + [1 - (3 + 2)]$	4 $[3 - (2 + 1)] + 4$
	M (SD)	M (SD)	M (SD)	M (SD)
Visual	3.3 (1.41)	2.7 (.69)	4.2 (.92)	3.6 (.66)
Tactile	13.2 (2.41)	8.7 (.59)	12.5 (1.05)	8.8 (1.53)

## Conclusions and Discussion

The first research question focused on the performance of braille and print readers. Joris needed more than twice as much time to read and process all expressions than the more experienced braille readers. He also made a reading error. On average, Sylvia and Michael needed about 3.5 as much reading and processing time for all items as the print readers. Both groups performed equally well on the items.

The second research question focused on tactile and visual reading strategies. As expected, the braille readers started reading the expression at the first braille cell. They had to reread (parts of) the expressions to precisely decode the braille characters, to sequentially build an overview over the expression, and to compensate for ineffective regressions (Loomis et al., 1991; Perea et al., 2015; Tobin & Hill, 2015). For all items, Sylvia started with a quick movement of the index fingers, from left to right, over the expression on the braille display to locate the end of the expression. Michael lingered, frequently, with his left index finger on an open bracket while reading with his right index finger. Both students started with a more conjoint reading strategy and ended with a more disjoint one. According to Breidegard and his colleagues (2006), this pattern suggests that they started with efficient and profound reading skills. These basic strategies helped them to read and solve the expressions. Joris, the less experienced braille reader, did not show such efficient strategies. In addition, the touch time charts show that the location of the braille cell is important for the relative amount of touch time. Dennis seemed, as did the other print readers, to have an overview over the expression almost immediately. The visual scan paths and the visual time charts show that brackets did not require much gaze time. This finding is in line with the study of Schneider and her colleagues (2012). In addition, print readers seemed to be tempted to make mistakes when the gaze direction was not in agreement with the calculation direction, which shows that the interaction between the syntax of the expression and reading directions can be complex (Schneider et al., 2012).

Although we did not investigate this interaction systematically, the think-aloud protocols of braille and print readers revealed very similar steps in processing the information and seemed to be guided by the algebraic structure of the expressions, a finding that is in agreement with the study of Fajardo-Flores and Archambault (2012). The braille readers were not able to efficiently align their reading strategies to the required solution procedures within the constraints of tactile reading, which resulted in tactile scan paths that contained many personal choices and required a lot of rereading. As a result, for each item, graphs of braille

readers were very different, while the graphs for print readers showed many similarities that could be related to the structure of the item. A limitation of the study is the small number of students and the particular type of mathematical expressions we used. A second limitation is that the braille readers, in contrast to what they were accustomed to, were not allowed to use synthetic speech. A third, technical limitation is that, during finger tracking, the markers of the two index fingers were occasionally too close to distinguish one from the other. In those cases, position data of the visible marker were used to manually repair such gaps.

This study adds to the small number of studies on ways to support braille readers in mathematics. An implication for teachers of students with visual impairments is that they be aware of the kind of problems that braille readers confront when they try to comprehend and solve mathematical problems. We recommend further experiments with similar research methods to investigate strategies of braille and print readers in mathematics. Findings from such studies should enable teachers to better support braille readers in mathematics and in successfully finishing their educational path. Finally, research on how braille readers perceive and process mathematical expressions also leads to insights that contribute to the learning of mathematics in general (Figueiras & Arcavi, 2014).

### **Authors' Note**

The study presented here was approved by the medical ethical committee of the Erasmus Medical Centre (MEC-2012-097 and MEC-2012-524) and adheres to the tenets of the Declaration of Helsinki (2013) for research involving human subjects. Informed consent was obtained from the subjects.

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