How reading braille is both like and unlike reading print

MEREDYTH DANEMAN

Erindale College, University of Toronto, Mississauga, Ontario, Canada

The letter detection errors of blind readers of braille were compared with those of sighted readers of print in order to determine whether braille can be read in units larger than the individual braille character. Sighted readers missed a disproportionate number of *hs* in the word *he* whether the prose was intact or scrambled, supporting Healy's (1976) conclusion that high-frequency words are read in units larger than the individual letter. By contrast, blind readers missed only a disproportionate number of *hs* in *he* when reading prose, suggesting that their detection failures were based on redundancy rather than unitization. Although the unit of perception for braille appears to differ from that for print, the factors underlying braille comprehension ability do not. Braille comprehension was correlated with listening comprehension and working memory capacity, a finding consistent with the visual reading literature which has shown that it is the higher level linguistic processes that tax working memory capacity and not the lower level visual word encoding processes that chiefly underlie individual differences in comprehending print.

This study addressed two questions regarding how blind adults read braille: Is there any evidence that braille can be read in units larger than the individual braille character? What accounts for individual differences in the comprehension abilities of braille readers?

Braille Reading Units

Much of the research on braille reading has focused on the issue of whether or not braille can be read in units larger than the individual letter or braille character. The bulk of the literature takes the position that it cannot. This position is based on knowledge about the functioning of the tactual perceptual system on which braille depends, as well as on observations of braille reading behavior. Braille is a system of raised dots arranged in a small 2 × 3 matrix. A minimum of one raised dot and a maximum of six allows for 63 discrete patterns of dots or braille characters, each tactually distinguishable from the other. In Grade 1 braille, each of the 26 letters of the alphabet is represented by a unique braille character; thus, for example, the 13-letter word *understanding* is represented by the sequential arrangement of the braille characters for its 13 letters: (u) (n) (d) (e) (r) (s) (t) (a) (n) (d) (i) (n) (g). In Grade 2 braille, some frequently recurring letter groups are represented in contracted form, that is, by one or at most two characters (e.g., one character for *ing*,

two for *under*); thus, for example, *understanding* is spelled with only five braille characters: ((under)) (st) (and) (ing). Even in its contracted form, braille is much more difficult to read than visual print, with experienced readers of braille averaging about 70 to 100 words per minute, compared with experienced readers of print who average 250 to 300 words per minute (Foulke, 1982; Nolan & Kederis, 1969). The most popular explanation for this difference is that the unit of perception for braille is the individual braille character (Millar, 1984; Nolan & Kederis, 1969), whereas the unit of perception for print can be larger than an individual letter and may even be the whole word (Haber, Haber, & Furlin, 1983; Healy, 1976, 1980; Johnson, 1975; Theios & Muise, 1977). The tactual perceptual window is much smaller than the visual perceptual window, and tactual information is best gathered by the continuous movement of cutaneous tissue, unlike visual information which is picked up during the pauses or fixations between eye movements (Foulke, 1982). Given the mechanics of the tactual perceptual system, braille characters are necessarily encountered in serial fashion and thus, the argument goes, are likely perceived in serial fashion too. Behavioral observations indicative of a character-by-character braille reading process include the finding that the time needed to identify a braille word depends on its length, both for familiar words and unfamiliar words (Nolan & Kederis, 1969), and the time needed to identify a braille word frequently exceeds the sum of the times needed to identify its component characters (Nolan & Kederis, 1969). Moreover, training in braille character recognition improves braille reading, whereas training in whole-word recognition does not (Nolan & Kederis, 1969).

This model of braille reading has not gone unchallenged. The position that perceptual units can be larger

This research was supported in part by Grant A2690 from the Natural Sciences and Engineering Research Council of Canada. I thank G. Grace and the staff at the Canadian National Institute for the Blind for their help in the recruitment of blind subjects and in the preparation of braille materials, Joan Collins and Murray Stainton for their help in data collection and analysis, and particularly Mark Hammond for his indispensable role in testing the blind subjects. Requests for reprints should be sent to M. Daneman, Department of Psychology, Erindale College, University of Toronto, Mississauga, Ontario L5L 1C6, Canada.

than the individual braille character is based on the belief that it is possible for an extended spatiotemporal pattern to emerge from a sequential exposure (Krueger, 1982; Kusajima, 1974). The empirical evidence advanced in favor of larger braille reading units is the finding by Nolan and Kederis (1969) that their braille readers could in fact recognize 10% to 20% of the words faster than their component letters, and the finding by Krueger (1982) that braille readers are faster at detecting a target letter in a word than in a nonword. Krueger (1982) interpreted his finding to mean that braille "is processed in neither an overly holistic fashion nor an overly analytical fashion" (p. 347). If processing were holistic, braille words would conceal their component letters, making letter search slower through words than nonwords. If processing were done character by character, then the search time through words and nonwords should be equivalent.

However, neither the Nolan and Kederis (1969) finding nor the Krueger (1982) finding constitutes clear-cut evidence that braille readers can use shape cues extending over more than one braille character. Because the effects were demonstrated for relatively long words (usually six letters or more), readers could have been using their lexical and orthographic knowledge to guess what the word and its constituent letters might be; they may not even have needed to feel all the letters to identify the word (Nolan & Kederis, 1969) or to decide on the presence or absence of a target letter (Krueger, 1982). To provide a stronger case for perceptual reading units that extend beyond the individual braille character, one needs a task that controls for guessing from context internal as well as context external to the word. The use of short words would limit the availability of internal context, that is, lexical or orthographic cues; a text-scrambling manipulation would eliminate the availability of external context, that is, semantic and syntactic cues. For these reasons, the letter detection task used by Healy (1976) is ideal for demonstrating that the size of the visual reading unit can be larger than the individual letter. The present study used a modified version of the Healy (1976) task to investigate the size of the braille reading unit.

In an elegant series of experiments, Healy and colleagues (Drewnowski & Healy, 1977; Goldman & Healy, 1985; Healy, 1976, 1980) showed that sighted readers of print are more likely to make letter detection errors on familiar words such as *the* and *and*. There are a number of explanations for why readers are more likely to miss the letter *t* in the word *the* than in other words such as *bathed*, *tend*, and *lantern*. The two most plausible ones are *redundancy* and *unitization*. According to the redundancy explanation, *the* is a highly redundant word both semantically and syntactically, so it is likely to be scanned only superficially or skipped over entirely. According to the unitization explanation, *the* occurs with such frequency in the language that it is "especially likely to be read as a unit or chunk rather than in terms of its component letters" (Healy, 1976, p. 235). Whereas both hypotheses predict that *t* should be missed more frequently in the word

the than in less common words, they make different predictions if the semantic and syntactic integrity of text is violated by scrambling the words: Redundancy predicts that the letter *t* would be as easily detected in *the* as in other words, whereas unitization predicts that the *t* in *the* would still be concealed because scrambling the words does not violate the integrity of the well-learned whole-word unit *the*. Since the latter prediction was confirmed for *the* and other highly familiar words, the findings have been interpreted as evidence that visual readers of print can recognize familiar words via units larger than the letter (Drewnowski & Healy, 1977; Healy, 1976).

To determine whether blind individuals can read in units larger than the individual braille character, the present study investigated whether there would be more letter detection failures for the letter *h* in the word *he* than in other word contexts. The reason for using the *h/he* task rather than the standard Healy (1976) *t/the* task had to do with the nature of Grade 2 braille. In Grade 2 braille, the letter *t* is not preserved in the word *the* because the contracted form for *the* is a single unique braille character; indeed, *he* is one of the few short high-frequency words that is not contracted. It was considered necessary to use Grade 2 braille, and hence the *h/he* variant, in the present study because most schools introduce Grade 2 braille from the start (Krueger, 1982; Nolan & Kederis, 1969), and because a pilot study revealed that adult blind subjects were uncomfortable reading the less familiar Grade 1 braille. Because *he* is less frequent and carries more meaning than *the*, a second experiment with regular print was conducted to determine whether *he* shows the same unitization effect in sighted readers that Healy (1976, 1980) demonstrated for *the*.

Braille Comprehension Ability

The work on braille reading ability has tended to investigate perceptual-motor aspects of the reading process for potential sources of individual differences between good and poor braille readers or between fast and slow braille readers. Some researchers have examined tactual scanning behavior to determine the extent to which factors such as the smoothness or style of hand and finger movements and the number and duration of regressive hand movements are related to braille reading competence (Critchley, 1953; Davidson, Wiles-Kettenmann, Haber, & Appelle, 1980; Fertsch, 1974; Kusajima, 1974). This research has parallels in the visual reading literature, which has shown a correlation between eye fixation patterns and reading ability (Nodine & Lang, 1971; Nodine & Simmons, 1974; Tillson, 1955). However, the most convincing interpretation of this correlation appears to be that poor eye movement control is a result, not a cause, of poor reading ability (Just & Carpenter, 1980; Stanley, 1978; Tinker, 1946, 1958). Such a conclusion is based on evidence from oculomotor training studies that were effective in altering subjects' eye movements but not in improving subjects' comprehension performance (Tinker, 1946, 1958) and from observations that poor readers' im-

mature eye movements do not generalize to nonreading scanning tasks such as picture scanning (Stanley, 1978). A similar conclusion about the relationship between hand movements and braille comprehension may be forthcoming. If the hand movements simply reflect the braille comprehension processes, other explanations for comprehension differences must be sought.

A second research approach has been to investigate possible differences between good and poor readers in the perceptual and phonological coding strategies used to recognize words (Foulke, 1982; Millar, 1984; Pring, 1982, 1984). One hypothesis is that only the skilled braille reader can utilize word shape cues, thereby obviating the need to recognize familiar words character by character. There is a parallel line of research in the area of visual reading ability that has emphasized the perceptual processes involved in visual word recognition as a key to comprehension success and failure (Hunt, Lunneborg, & Lewis, 1975; Perfetti & Hogaboam, 1975; Stanovich, 1980). However, recent studies have suggested that higher order linguistic factors, rather than visual word encoding, may be the major bottleneck in reading, at least for adult readers (Daneman & Carpenter, 1980; Jackson & McClelland, 1979; Sticht, 1972). Jackson and McClelland (1979) showed that a measure of listening comprehension ability accounted for much more of the variance in reading comprehension ability than did a measure of the speed with which adults could access verbal codes from visual material. Daneman and Carpenter (1980) also argued that a significant amount of individual difference is common to both reading and listening and that comprehension processes that tax working memory capacity may be responsible for difficulties individuals have in either reading or listening to verbal discourse. Despite the striking differences between tactually dependent braille and visually dependent print, both codes must yield information that is ultimately mapped onto the same linguistic system. Consequently, it is likely that braille comprehension ability is also linked to general linguistic factors and working memory capacity. The present study tested these predictions by investigating the relationship between measures of braille comprehension ability and measures of listening comprehension and working memory capacity.

METHOD

Experiment 1: Braille

Subjects. The subjects were 31 blind adults living in the Toronto area and recruited through two Canadian organizations for the blind: The Canadian National Institute for the Blind (CNIB) and The Blind Organization of Ontario for Self-help Tactics (BOOST). The age range was 23 years to 59 years ($M=37$ years). All subjects were legally and functionally blind, but could be classified into two groups according to the onset of their blindness. There were 20 congenitally blind subjects who had received no instruction in reading or writing English orthography. The onset of blindness for the remaining 11 subjects varied from early childhood to middle adulthood; however, what was common to all these subjects was that they had received at least some formal instruction in reading and/or writing regular English print. A striking difference between the two groups

was that the first group was signed with a series of squiggles or scribbles that contained virtually no identifiable alphabetic characters, whereas the noncongenitally blind subjects' signatures were perfectly legible. The subjects were tested individually over two sessions lasting approximately 1 h each, and were paid for their participation. They were given the seven tasks described below.

Letter detection task. Subjects read two short passages and searched for instances of the braille letter *h*. One passage was in regular prose form, and the other was in scrambled-word form.

The materials consisted of two narrative passages, each approximately 110 words in length. Two braille forms were created for each passage: a prose form and a scrambled form. The prose form was created by transcribing the passage into standard Grade 2 braille with the use of an Apple computer, and printing it double-spaced on thick 12×11 in. (30×28 cm) paper. The scrambled form was derived from the prose by maintaining the location of all punctuation marks and *hes* and changing the location of all other words so that they were randomly ordered. Subjects who received the first passage in prose form received the second in scrambled form, and vice versa. The order of presentation of prose and scrambled forms was counterbalanced across subjects.

Although the first passage contained 40 *hs* altogether, in contracted Grade 2 braille it contained 27 *hs*, 8 of them occurring in the word *he*. Similarly, the second passage contained 52 *hs* altogether, but in contracted braille it contained 25 *hs*, 7 of them occurring in the word *he*. Table 1 shows the two prose passages in regular print, with the instances of *h* that are preserved in Grade 2 braille underlined. Note that although *h* occurs in many high-frequency words in regular print (e.g., *his*, *that*, *the*, *when*), it is not preserved in these contexts in Grade 2 braille. This means that the *non-he* instances of *h* tend to occur in less frequent words than *he*, allowing for the crucial comparison of letter detection errors for *h* in high-frequency *he* versus in lower frequency other words. Also, the proportion of *he* to remaining *non-he* *h*-words was roughly equivalent to the *the/non-the* proportions used by Healy (1976).

The subjects were told to read each passage with their normal reading style and at their normal reading rate so that they would

Table 1
Passages for *h* Detection Task Used in Experiments 1 and 2

1. When Howard Johnson bought miles of uninhabitable hills in Ohio, news leaked out that he had* happened upon vast deposits of sapphire. He made no effort to sell stock; it was begged from his hands, and he merely chose those whom he wished to help. His talent has been called phenomenal. He would buy failing industries and they would rise from their ashes like the mythical Phoenix. This was not just a lucky phase; the rhythm of market forces did not impede him. * He enhanced his fortune with every deal he touched and every step he made. However, those who hated him* most were never hesitant to ride on his honest talent.

2. When John Hinds saw that the conductor had* collapsed from exhaustion ahead of the engine, he knew that there was nothing that could be done there any longer. Dimly comprehending that the train needed help, he climbed down the hopper unhesitatingly, even though he knew that the lineman's phone was hours away. He could hear the howls of a fox in the deserted hills as he let himself drop to the ground. He stood still and, in the echoing silence, he heard the rustle of tumbleweeds inhabiting the plains, like the hysterical laughter of an invisible army made free to move while the train was held motionless.

*The braille character for *h* (raised dots 1, 2, 5) stands for several other letter groups in Grade 2 braille; for example, the contracted word *had* consists of two characters, the second of which is the same character as the one for *h*, and the contracted word *him* consists of two characters, the first of which is the same character as the one for *h*. Since subjects may or may not have treated such instances as *hs*, the three instances of these words in passage 1 and the one instance in passage 2 were not included in the analysis.

comprehend the passage, and to search for instances of the letter *h* as they read. When they encountered an instance of the letter *h*, they were to signal this to the experimenter by tapping the letter with their reading finger(s). Before receiving the two experimental passages, the subjects were given a practice passage so that they could become comfortable with the procedure.

To monitor the tapping and accurately record missed taps, the experimenter used a visual print analogue of the braille passage with all the *h* locations clearly marked. When a subject failed to detect an *h*, the experimenter circled the corresponding location on the printed version. The experimenter had no difficulty determining which *h* a subject was indicating by any one tap, because successive instances of *h* on a line of braille text were never less than 1 in. apart (most were 3 or more inches apart), and subjects made almost no false alarms to non-*h* braille characters.

Because braille sheets can be worn down by excessive use, making letter detection easier or harder because of tapped-down letter groups, several precautions were taken to minimize wear and tear. Firm cardboard was used, and duplicate copies were made of all braille passages. Since there were four passage forms (passage 1-prose, passage 1-scrambled, passage 2-prose, passage 2-scrambled), and only half the subjects were given any one passage form (e.g., those given passage 1-prose were not given passage 1-scrambled), this meant that only one-fourth of the subjects were exposed to any one copy of a passage. Since there was no evidence from the data to suggest that subjects tested later in the experiment found the detection task easier or more difficult than subjects tested earlier, wear and tear was not a problem.

As in the standard Healy (1976) paradigm, comprehension questions were not administered following letter detection; although this leaves open the possibility that subjects were not reading the prose passages for meaning, a recent study by Proctor and Healy (1985) found the same pattern of letter detection errors in a prose task whether or not comprehension was required.

Braille passage comprehension. The test was adapted from the Nelson-Denny reading test for sighted subjects. A 200-word passage about fungi and the four related multiple-choice questions were transcribed into single-spaced Grade 2 braille using an Apple computer. The subjects were given the passage to read, followed immediately by the questions to which they responded orally. The time required by subjects to read the passage, translated into words per minute, served as a measure of their braille reading rate. The experimenter measured reading time with a stopwatch, starting the timer when a subject touched the first braille character and stopping the timer when the subject touched the last braille character.

Braille comprehension monitoring. As an additional test of braille comprehension ability, the subjects were given two 350-word expository texts in Grade 2 braille, and their task in each case was to read the passage carefully while at the same time trying to identify words that had been misspelled. Each time they encountered an incorrect word, they were to tap it with their reading finger. The subjects were warned that some of the errors would be difficult to detect, because the misspelling produced a real English word. In fact, in this task, all misspellings were themselves legal English words (e.g., *six* misspelled as *sex* in the sentence, *At present sex percent of married adults are only children*). Consequently, misspellings could be detected only if the reader understood the semantic and syntactic context in which the error word occurred, making the task a sensitive measure of comprehension ability. Indeed, high correlations have been found between performance on this kind of comprehension monitoring task and performance on standard tests of reading comprehension ability (Daneman, Collins, & Stainton, 1987). In the braille version used here, each passage contained 24 misspelled words. All misspellings were introduced by changing only one letter in a word, with neither the substituted letter nor the original letter involved in a contraction, and with the resulting word

always semantically or semantically and syntactically inconsistent with the context.

The subjects were given a score out of 48 for the number of misspelled words they identified. The subjects' braille passage comprehension scores and braille comprehension monitoring scores were converted to standard scores and then combined to obtain an overall braille comprehension ability score.

Listening comprehension. The listening comprehension test was patterned after the braille passage comprehension test. A 200-word passage about economics from the Nelson-Denny test was recorded by an adult male onto a cassette tape. The subjects listened to the tape and then answered four multiple-choice questions about it. The questions were presented on the tape immediately after the subjects heard the passage; however, to avoid the memory demands required for holding a question and its five choices in memory, the subjects were also provided with a copy of the questions in braille to which they could refer while giving their verbal response to each question.

Braille span. This test and the listening span test to be described next were patterned after the measures devised by Daneman and colleagues to assess the simultaneous processing and storage capacity of working memory (Daneman & Blennerhassett, 1984; Daneman & Carpenter, 1980, 1983; Daneman & Green, 1986). Unlike digit span and word span, which tax storage only and which are not correlated with reading ability (Perfetti & Lesgold, 1977), Daneman's working memory span tests tax processing as well as storage and are highly correlated with the reading and listening comprehension ability of sighted subjects (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Daneman & Carpenter, 1980, 1983; Daneman & Blennerhassett, 1984; Masson & Miller, 1983). The working memory span tests used in the present study resembled most closely the variant used by Daneman and Blennerhassett (1984).

For braille span, the subjects were given increasingly longer sets of unrelated sentences to read aloud. At the end of each set, they had to recall verbatim each sentence of the set. The test was constructed with 18 unrelated sentences, 9 to 17 words in length. Two examples are *Venice is like eating an entire box of chocolates in one go*, and *The nearest some people ever come to gardening is digging up the past*. Each sentence was printed in Grade 2 braille and pasted on an 8×5 in. (20×12.5 cm) index card. The cards were arranged in three sets each of 1, 2, and 3 sentences, with a blank card inserted to mark the beginning and end of each set. The experimenter presented one card at a time, and the subjects read the sentence aloud. For sets containing more than 1 sentence, the subjects were required to read them in quick succession. At the end of each set, they tried to recall, verbatim, each sentence in the set. If they could not remember the exact wording, they were encouraged to repeat as much of each sentence as they could. They were encouraged to recall the sentences in the order presented, but if they could not remember the order, to repeat them in any order. A subject's braille span score was the total number of words recalled out of a maximum of 230 words. Before testing, the subjects were given several practice items to ensure that they understood the instructions.

Listening span. The listening span test was identical to the braille span test, except that subjects listened to sentences rather than read them. The test was constructed with 18 new sentences, 9 to 17 words in length, recorded on a cassette tape recorder in three sets each of 1, 2, and 3 sentences. A beep signaled the end of a set. A subject's listening span score was the total number of words recalled out of a maximum of 243 words.

Braille proofreading. This task was similar to the braille comprehension monitoring task in that the subjects read two 350-word passages of expository prose and tried to identify misspelled words. There were 96 misspelled words, each created by changing only one letter in a word. However, in this task all of the 96 misspellings produced nonwords (e.g., *kinf* for *kind* in the sentence, *One could argue that the bulk of intelligence testing is not the kinf*

that occurs in psychologists' consulting rooms). Consequently, misspellings could be detected on the basis of knowledge about the spelling of English words and did not demand an understanding of the syntactic and semantic context in which the error word occurred. The subject was given a score out of 96 for the number of misspelled words he/she detected.

In Session 1, the subjects were given the listening comprehension and braille comprehension tasks, followed by the listening span and braille span tasks. In Session 2, they were given the braille comprehension monitoring and braille proofreading tasks, followed by the letter detection task. As a measure of practice at braille reading, the subjects were also asked to estimate the average number of hours per week they spent reading braille.

Experiment 2: Print

Subjects. The subjects were 32 University of Toronto undergraduates with normal or corrected-to-normal vision. The subjects were tested individually in a single session and received course credit or payment for their participation.

Letter detection tasks. The subjects performed the identical *h* detection task as did the blind subjects in Experiment 1, except that the sighted subjects read regular double-spaced print rather than braille, and signaled instances of the letter *h* by circling them with a pencil rather than by tapping them with a finger. Although more *hs* were present in the print than in the braille passages, only those instances that remained intact in Grade 2 braille (see Table 1) were used in the analysis.

Following the *h* detection task, the subjects were also given a standard Healy (1976) *t* detection task. They were required to read two 100-word passages and circle all instances of the letter *t*. In one passage, there were 40 instances of the letter *t*, 10 of them in the word *the*. In the second passage, there were 41 instances of the letter *t*, 11 of them in the word *the*. As in the *h* task, subjects who saw the first passage in prose form saw the second in scrambled-word form, and vice versa. The order of presentation was counter-balanced across subjects.

RESULTS AND DISCUSSION

Reading Units

There is no evidence from the letter *h* detection task to suggest that braille can be read in units larger than the individual braille character. Take first the data from the congenitally blind braille readers. As seen in Table 2, congenitally blind readers did miss more instances of *h* in the highly familiar word *he* than in other kinds of words, but only when they were reading intact prose. When reading prose, they missed on average 14.2% of the *hs* in *he*, as opposed to only 2.7% of the *hs* in other kinds of words;

however, when reading scrambled words, they missed only 2% of the *hs* in *he*, which was as low as their 3.5% error rate for *hs* in other kinds of words [$F(1,19) = 5.56$, $MSe = 152$, $p < .03$]. This significant interaction between passage type and word type is more consistent with a redundancy explanation than a unitization one, because redundancy predicts that the higher error rate for *h* in *he* will occur only when *he* is predictable from the semantic and syntactic context, whereas unitization predicts high error rates for the familiar unit *he* regardless of semantic and syntactic predictability.

The present results cannot be explained in terms of any idiosyncratic properties of the *he/non-he* comparison, because the sighted subjects in Experiment 2 performed similarly for the *h/he* task as for the *t/the* task, and in both cases the results replicated Healy's (1976) unitization pattern. As seen in Table 2, sighted subjects were more likely to miss *h* in *he* than in other words [$F(1,31) = 11.74$, $MSe = 206$, $p < .01$], and this was true for both prose and scrambled words (interaction $F < 1$). Although readers made more errors on the *t* detection tasks than on the *h* detection task [$F(1,31) = 16.65$, $MSe = 363$, $p < .01$], the pattern of results for *t* was identical: subjects were more likely to miss instances of *t* in the word *the* than in other words [$F(1,31) = 24.35$, $MSe = 296$, $p < .01$], and this was true for both prose and scrambled words (interaction $F < 1$). It is interesting to note that the percentages of letter detection errors on *the* (24.6%) and *he* (12.7%) obtained in this study are quite similar to those reported by Healy (1980) for *the* (38%, Experiment 2, p. 52) and for common words (14.2%, Experiment 3, p. 54), respectively. Given that *he* yielded the identical pattern of data as did *the* in the present experiment, and a similar percentage of detection failures as did comparable Healy data, it seems reasonable to assume that *he* behaves like other common short words.

An analysis of variance that combined the *h* detection data for the 20 congenitally blind subjects and the 32 sighted subjects revealed no differences between braille and print readers in overall detection errors ($F < 1$), but did reveal a significant print type $\times$ passage type $\times$ word type interaction [$F(1,50) = 7.56$, $MSe = 90$, $p < .01$], thus providing statistical support for the conclusion that congenitally blind subjects and sighted subjects show different patterns of detection errors for the letter *h*. When

Table 2
Error Percentages for Letter Detection Tasks in Experiments 1 and 2

Task	Experiment 1 (Braille)				Experiment 2 (Print)	
	Blind (Congenital)		Blind (Noncongenital)		Sighted	
	Prose	Scrambled	Prose	Scrambled	Prose	Scrambled
<i>h</i> Detection						
<i>He</i>	14.2	2.0	0.0	3.7	10.2	13.3
Other	2.7	3.5	1.5	0.5	2.4	3.7
<i>t</i> Detection						
<i>The</i>					25.3	23.9
Other					9.4	9.8

congenitally blind braille readers fail to detect the letter *h* in *he*, it appears to be because contextual predictability or redundancy allows them to skip over *he* or process *he* less thoroughly; when sighted readers fail to detect the letter *h* in *he*, it is because they read *he* as a whole word rather than in terms of its component letters. Since blind readers showed no evidence of unitization for a two-character word such as *he*, it seems reasonable to assume that they would be even less likely to read longer words as single units.

The 11 noncongenitally blind braille readers did not show a redundancy effect like that of the congenitally blind readers; however, of paramount importance to the question addressed in the present study, they also did not show evidence of reading in units larger than the individual braille character. As seen in Table 2, their overall error rate was low; in fact, they made no detection errors for the word *he* in prose (a pattern inconsistent with redundancy or unitization) and only 3.7% errors for the word *he* in the scrambled passage (a pattern inconsistent with unitization). The three-way interaction between onset of blindness, type of passage, and type of word was significant [$F(1,29) = 5.32$, $MSe = 105$, $p < .03$] in an analysis of variance that included the data for all 31 blind subjects. Of course, it is difficult to make any firm conclusions about the noncongenital group, given the small sample and the few errors. However, the noncongenitally blind subjects were much slower braille readers than were the congenitally blind ones, with an average reading rate of only 44 words per minute, compared with the congenitally blind subjects' average reading rate of 73 words per minute [$t(29) = 3.43$, $p < .01$]; this suggests that the noncongenitally blind braille readers were able to avoid missing *h* in *he* precisely because of their slow character-by-character mode of reading.¹ As will be seen in the next section, however, despite their very slow reading rate, the noncongenitally blind subjects were not poorer on the two braille comprehension measures.

Braille Comprehension Ability

Table 3 contains the means and standard deviations for each individual-differences measure. Table 4 shows how the different measures are correlated with braille comprehension ability and braille reading rate.² Whereas the unit of perception for braille appears to differ from that

for print, the factors underlying braille comprehension ability do not differ from those underlying visual reading comprehension ability. As predicted, the ability to comprehend verbal material written in braille was significantly and positively correlated with the ability to comprehend verbal material presented orally, with $r_s(29)$ ranging from .39 to .49 (all $ps < .05$). Also as predicted, the ability to comprehend braille was highly correlated with the two measures of working memory capacity, braille span and listening span, with $r_s(29)$ ranging from .48 to .66 (all $ps < .01$). It is interesting to note that listening span was as good a predictor of braille comprehension ability as was braille span, with the two span measures themselves highly correlated [$r(29) = .75$, $p < .01$]. This suggests that the major bottleneck in braille comprehension may not reside with the tactual processes involved in decoding braille characters. Additional support for this contention comes from the finding that the ability to comprehend braille was not at all correlated with the ability to find misspelled nonwords or the tendency to miss detecting instances of the letter *h* in *he* and other *h* words (all $ps > .10$). Both the proofreading task and the letter detection task seem to involve perceptual processes at the level of the individual word rather than memory-intensive linguistic processes that extend beyond the word. The finding that these two braille word tasks were less related to braille comprehension ability than were the two non-braille but higher level tasks (listening comprehension and listening span) is consistent with the literature on visual reading ability, which has shown that visual word encoding processes are not the major source of individual differences in adult reading comprehension ability (Daneman & Carpenter, 1980; Jackson & McClelland, 1979). A more important source of individual differences is working memory capacity, presumably because working memory capacity reflects how much verbal material an individual will be able to keep accessible as he/she proceeds through text, and consequently how easily the individual will be able to integrate the successively encountered ideas and develop a coherent representation of the text (Daneman & Carpenter, 1980, 1983; Kintsch & van Dijk, 1978).

With braille reading rate rather than braille comprehension as the criterion variable, the pattern of correlations was reversed. As seen in Table 4, neither listening com-

Table 3
Mean Performance and Standard Deviation for Individual-Differences Measures Used in Experiment 1

	Blind (Congenital) ($N=20$)		Blind (Noncongenital) ($N=11$)		Blind (Combined) ($N=31$)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Braille Passage Comprehension (max=4)	2.6	1.2	2.7	1.2	2.7	1.2
Braille Comprehension Monitoring (max=48)	41.4	5.2	41.9	6.7	41.6	5.7
Braille Reading Rate (words/min)	73.0	20.3	44.4	22.6	63.2	24.8
Listening Comprehension (max=4)	3.2	0.7	2.8	1.2	3.0	1.0
Braille Span (max=230)	160.8	33.2	153.2	41.3	158.1	35.8
Listening Span (max=243)	162.4	26.4	154.7	29.2	159.7	27.2
Braille Proofreading (max=96)	88.4	4.2	89.9	3.3	88.9	3.9
Braille Letter Detection Errors (percent)	5.6	8.1	1.4	1.7	4.1	6.9
Reported Braille Practice (hours/week)	14.3	14.9	10.8	13.4	13.1	14.2

Table 4
Correlations Among Tasks in Experiment 1

Individual-Differences Measures	Braille Comprehension Measures			Braille Reading Rate (words per minute)
	Passage Comprehension	Comprehension Monitoring	Overall Comprehension	
Comprehension Sensitive				
Listening comprehension	.39*	.43*	.49†	.32
Braille span	.58‡	.52†	.64‡	.18
Listening span	.62‡	.48†	.66‡	.16
Word Sensitive				
Proofreading	.07	.25	.18	-.03
Letter detection	.13	.11	.15	.38*
Other Variables				
Reported braille practice (hours/week)	.06	.21	.17	.36*
Onset of blindness (congenital vs. noncongenital)	.03	.04	.06	-.55†
Age at testing	-.09	.19	.09	-.38*

* $p < .05$. † $p < .01$. ‡ $p < .001$.

prehension nor working memory span was significantly correlated with braille reading rate. Even the correlation between braille reading rate and overall braille comprehension ability did not reach significance [$r(28) = .20$, $p > .10$]. Although not related to these comprehension-sensitive measures, braille reading rate was correlated with the more perceptual task of letter detection; as seen in Table 4, faster readers were more likely to miss instances of the letter *h* [$r(28) = .38$, $p < .05$]. Braille reading rate was also related to two individual differences variables that reflected experience with braille: congenitally blind readers were faster at braille than readers who lost their vision after birth and presumably began reading braille later in life [$r(28) = -.55$, $p < .01$], and those readers who reported spending more hours a week reading braille were also faster [$r(28) = .36$, $p < .05$]. This general pattern of results suggests that the mechanisms underlying braille reading rate differ from those underlying braille reading comprehension ability. Again, the finding is consistent with a recent study of visual reading ability which showed that reading rate "varies with visual word processing, while reading comprehension varies with nonvisual linguistic processing" (Palmer, MacLeod, Hunt, & Davidson, 1985, p. 59).

CONCLUSION

It is not surprising that basic and applied research on braille reading skill has been concerned largely with the tactual perceptual processes. Indeed, braille reading is very difficult and slow because of the nature and limitations of the tactual perceptual system on which it relies. One consequence of tactual perception is that braille can be read only character by character (Foulke, 1982; Nolan & Kederis, 1969), as the present study corroborated even for two-character words such as *he*. However, what the present study also showed is that the tactual-perceptual properties seem to limit the speed with which

braille can be read, but not the skill with which the message represented by the braille can be integrated and understood. What the present study suggests is that it is a general verbal processing capacity common to both reading and listening that is responsible for individual differences in braille reading comprehension ability. An individual-differences theory that stresses tactual perceptual processes involved in word recognition may not capture a significant source of variance that is common to both reading and listening. Although the present conclusions are consistent with current thinking in the general field of reading comprehension ability, this and other evidence is still correlational. Consequently, further research is needed to determine precisely how and when working memory capacity influences the comprehension processes of readers of braille and readers of print.

REFERENCES

- BADDELEY, A. D., LOGIE, R., NIMMO-SMITH, I., & BRERETON, N. (1985). Components of fluent reading. *Journal of Memory & Language*, 24, 119-131.
- CRITCHLEY, M. (1953). Tactile thought with special reference to the blind. *Brain*, 76, 19-35.
- DANEMAN, M., & BLENNERHASSETT, A. (1984). How to assess the listening comprehension skills of prereaders. *Journal of Educational Psychology*, 76, 1372-1381.
- DANEMAN, M., & CARPENTER, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning & Verbal Behavior*, 19, 450-466.
- DANEMAN, M., & CARPENTER, P. A. (1983). Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 9, 561-584.
- DANEMAN, M., COLLINS, J., & STANTON, M. (1987, November). *Phonological processes in reading and proofreading*. Paper presented at the 28th Annual Meeting of the Psychonomic Society, Seattle, Washington.
- DANEMAN, M., & GREEN, I. (1986). Individual differences in comprehending and producing words in context. *Journal of Memory & Language*, 25, 1-18.
- DAVIDSON, P. W., WILES-KETTENMANN, M., HABER, R. N., & APPELLE, S. (1980). Relationship between hand movements, read-

- ing competence and passage difficulty in braille reading. *Neuropsychologia*, **18**, 629-635.
- DREWNOWSKI, A., & HEALY, A. F. (1977). Detection errors on the and and: Evidence of reading units larger than the word. *Memory & Cognition*, **5**, 636-647.
- FERTSCH, P. (1974). An analysis of braille reading. *Outlook for the Blind*, **240**, 128-131.
- FOULKE, E. (1982). Reading braille. In W. Schiff & E. Foulke (Eds.), *Tactual perception: A source book* (pp. 168-208). New York: Cambridge University Press.
- GOLDMAN, H. B., & HEALY, A. F. (1985). Detection errors in a task with articulatory suppression: Phonological recoding and reading. *Memory & Cognition*, **13**, 463-468.
- HABER, L. R., HABER, R. N., & FURLIN, K. (1983). Word length and word shape as sources of information in reading. *Reading Research Quarterly*, **18**, 165-189.
- HEALY, A. F. (1976). Detection errors on the word the: Evidence for reading units larger than letters. *Journal of Experimental Psychology: Human Perception & Performance*, **2**, 235-242.
- HEALY, A. F. (1980). Proofreading errors on the word the: New evidence on reading units. *Journal of Experimental Psychology: Human Perception & Performance*, **6**, 45-57.
- HUNT, E., LUNNEBORG, C., & LEWIS, J. (1975). What does it mean to be high verbal? *Cognitive Psychology*, **7**, 194-227.
- JACKSON, M. D., & MCCLELLAND, J. L. (1979). Processing determinants of reading speed. *Journal of Experimental Psychology: General*, **108**, 151-181.
- JOHNSON, N. F. (1975). On the function of letters in word identification: Some data and a preliminary model. *Journal of Verbal Learning & Verbal Behavior*, **14**, 17-29.
- JUST, M. A., & CARPENTER, P. A. (1980). A theory of reading: From eye-fixations to comprehension. *Psychological Review*, **87**, 329-354.
- KINTSCH, W., & VAN DIJK, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review*, **85**, 363-394.
- KRUEGER, L. E. (1982). A word-superiority effect with print and braille characters. *Perception & Psychophysics*, **31**, 345-352.
- KUSAJIMA, T. (1974). *Visual reading and braille reading: An experimental investigation of the physiology and psychology of visual and tactual reading*. New York: American Foundation for the Blind.
- MASSON, M., & MILLER, J. A. (1983). Working memory and individual differences in comprehension and memory of text. *Journal of Educational Psychology*, **75**, 314-318.
- MILLAR, S. (1984). Strategy choices by young braille readers. *Perception*, **13**, 567-579.
- NODINE, C. F., & LANG, N. J. (1971). The development of visual scanning strategies for differentiating words. *Developmental Psychology*, **5**, 221-232.
- NODINE, C. F., & SIMMONS, F. G. (1974). Processing distinctive features in the differentiation of letterlike symbols. *Journal of Experimental Psychology*, **103**, 21-28.
- NOLAN, C., & KEDERIS, C. (1969). *Perceptual factors in braille word recognition*. New York: American Foundation for the Blind.
- PALMER, J., MACLEOD, C. M., HUNT, E., & DAVIDSON, J. E. (1985). Information processing correlates of reading. *Journal of Memory & Language*, **24**, 59-88.
- PERFETTI, C. D., & HOGABOAM, T. W. (1975). The relationship between single word decoding and reading comprehension skill. *Journal of Educational Psychology*, **67**, 461-469.
- PERFETTI, C. D., & LESGOLD, A. M. (1977). Discourse comprehension and individual differences. In P. Carpenter & M. Just (Eds.), *Processes in comprehension* (pp. 141-183). Hillsdale, N.J.: Erlbaum.
- PRING, L. (1982). Phonological and tactual coding of braille by blind children. *British Journal of Psychology*, **73**, 351-359.
- PRING, L. (1984). A comparison of the word recognition processes of blind and sighted children. *Child Development*, **55**, 1865-1877.
- PROCTOR, J. D., & HEALY, A. F. (1985). A secondary-task analysis of a word familiarity effect. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 286-303.
- STANLEY, G. (1978). Eye movements in dyslexic children. In G. Stanley & K. W. Walsh (Eds.), *Brain impairment: Proceedings of the 1977 Brain Impairment Workshop*. Victoria, British Columbia, Canada: Dominion Press.
- STANOVICH, K. E. (1980). Toward an interactive-compensatory model of individual differences in the development of reading fluency. *Reading Research Quarterly*, **16**, 32-71.
- STICHT, T. G. (1972). Learning by listening. In P. O. Freedle & J. B. Carroll (Eds.), *Language comprehension and the acquisition of knowledge* (pp. 285-314). Washington, DC: Winston.
- THEIOS, J., & MUISE, J. G. (1977). The word identification process in reading. In N. J. Castellan, D. B. Pisoni, & G. R. Potts (Eds.), *Cognitive theory* (Vol. 2, pp. 289-321). Hillsdale, NJ: Erlbaum.
- TILLSON, M. W. (1955). Changes in eye-movement pattern. *Journal of Higher Education*, **26**, 442-445.
- TINKER, M. A. (1946). The study of eye movements in reading. *Psychological Bulletin*, **43**, 93-120.
- TINKER, M. A. (1958). Recent studies of eye movements in reading. *Psychological Bulletin*, **55**, 215-231.

NOTES

1. Although braille reading rate was based on time to read the braille comprehension passage rather than on time to perform the letter detection task itself, it would appear that braille reading rate is relatively stable across tasks because subjects were also timed on the braille comprehension monitoring task and the two reading time measures were highly correlated [$r(28) = .88, p < .01$].

2. The braille reading rate of one noncongenitally blind subject was not recorded due to technical malfunctioning of the timer. Consequently, all the correlations involving braille reading rate were based on 30 subjects instead of 31.

(Manuscript received August 3, 1987;

revision accepted for publication February 17, 1988.)