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The association between tactile, motor and cognitive capacities and braille reading performance: a scoping review of primary evidence to advance research on braille and aging

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ABSTRACT

Purpose: As the prevalence of age-related visual impairment increases, a greater understanding of the physiological and cognitive capacities that are recruited during braille reading and the potential implications of age-related declines is required.

Methods: This scoping review aimed to identify and describe primary studies exploring the relationship between tactile, motor and cognitive capacities and braille reading performance, the instruments used to measure these capacities, and the extent to which age is considered within these investigations. English peer-reviewed articles exploring the relationship between these capacities and braille reading performance were included. Articles were screened by two researchers, and 91% agreement was achieved ($kappa = 0.84$ [0.81, 0.87], $p < 0.01$).

Results: 2405 articles were considered of which 36 met the inclusion criteria. Fifteen investigated the relationship between tactile capacities and braille reading performance, 25 explored motor capacities, and 5 considered cognitive capacities. Nineteen instruments were used to measure tactile capacity, 4 for motor dexterity, and 7 for cognitive capacity. These studies focus on younger participants and on those who learned braille early in life.

Conclusions: Although this overview underscores the importance of tactile perception and bimanual reading, future research is needed to explore the unique needs of older adults who learn braille later in life.

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KEYWORDS

Aging; blindness; braille; reading; rehabilitation; vision; low



► IMPLICATIONS FOR REHABILITATION


- The studies in this review underscore the importance of developing both haptic tactile perception and efficient hand reading patterns early in the braille learning process.
- Practitioners should consider whether specific pre-braille readiness activities can be used to address the unique needs of older adults who may experience tactile, motor or cognitive declines.
- Most of the studies in this review require replication before they should serve as reliable clinical guidelines; however, braille reading (like print) is a complex process that draws on multiple capacities that should be developed in unison.
- The studies in this review focus heavily on younger participants and on those who learned braille early in life, and highlight the need for future research on braille and aging.

Introduction

Tactile sensitivity, manual dexterity and cognitive capacities are vital components of efficient braille reading [1,2]. Many of these physiological and cognitive capacities are known to decline as part of the typical aging process [3]. While there is a broad scope of literature centered on braille literacy and childhood [2,4–6], there is insufficient evidence on the extent to which age-related declines in these capacities will effect braille reading outcomes. In recent decades, a variety of instruments have been developed to measure tactile, motor and cognitive capacities in blind

individuals and to explore the relationship between these measures and braille reading outcomes (for example, see [7–10]). However, these studies are sparse and have given rise to inconsistent findings depending on the instruments that are used, even when those instruments purportedly measure the same underlying capacity. For example, both Bola [11] and Veispak [12,13] explored the association between passive tactile acuity (using the Grating Orientation Test [14]) and braille reading speed, though Veispak observed a relationship while Bola did not. Thus far, there is no research which describes and summarizes these findings

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 Supplemental data for this article can be accessed [here](#).

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within a single comprehensive review. As the prevalence of age-related visual impairment continues to increase [15,16], there are growing calls for research on braille and aging and for the development of evidence-based practices that best support the needs of older adults who pursue braille [17]. It is possible that older adults with impaired tactile, motor or cognitive capacities may benefit from specific pre-braille readiness activities designed to target their unique needs [17]. Similarly, research is needed to ensure that clinical decisions are not based upon conjecture and overarching generalizations about aging, such as the prevailing belief among some prospective clients and rehabilitation practitioners that older adults are unable to pursue braille due to reduced tactile sensitivity [17,18]. The objectives of this review are to provide an overview of primary studies that explore the relationship between tactile, motor and cognitive capacities and braille reading performance in order to consolidate available research as a precursor to future studies that will build upon this evidence.

The ability to read is necessary for the completion of common daily tasks, from identifying household products to reading prescriptions, documents and instructions, and is closely tied to feelings of self-competence and independence for individuals who acquire a visual impairment [19,20]. In fact, reading-related difficulties are among the most common reasons for referral to low vision rehabilitation services [21,22]. Braille, a tactile system of reading and writing, provides a non-visual alternative to print for those with significant or fluctuating visual impairments or for those who have a degenerative visual condition [19]. As a literacy medium, it provides access to spelling, punctuation and other grammatical nuances that are often difficult to access through auditory-based methods alone [23]. Moreover, for the growing population of individuals with acquired dual sensory impairment (concurrent vision and hearing loss), braille may be the *only* vehicle through which communication becomes possible [24].

The reading of braille draws on the somatosensory cortex responsible for processing tactile perception, the motor cortex for fine movements of the fingers and hands, and much like visual reading, the cognitive functions of memory, sustained attention, information processing and comprehension [25]. Tactile information is perceived by a variety of peripheral touch receptors that transmit information from the distal pads of the fingertips to the central nervous system. The combined information when a reader lightly slides their fingers across a page of braille leads to the ability to discriminate braille characters [3]. Unlike print reading, braille reading can only occur haptically, through the smooth and constant movements of the reading hands, and disruption to movement will necessarily impede perception [1,26]. Impairments in one or both hands or instability stemming from degenerative disease may consequently impede tactual perception and reading speed [27]. Braille reading differs from print in that characters are read sequentially as the fingers move across a line rather than being perceived simultaneously during a single saccadic gaze. New or less proficient braille readers must retain each successive symbol in working memory to build a representation of the word in question [23,28–31], initially placing a greater emphasis on working-memory [17,32]. Conversely, more proficient or experienced braille readers with greater reading fluency are able to draw on lexical, perceptual and contextual cues to facilitate faster reading and comprehension [33–35].

Normal aging is associated with steady declines in tactile acuity, fine motor dexterity, and cognitive functions, including working-memory and sustained attention [3]. Tactile acuity of the fingertips has been shown to decrease with age [7,36], particularly

among the sighted who lack a lifetime of tactile experience [37], and this can be further impaired by neuropathic comorbidities such as diabetes [25]. Declines in fine and gross motor dexterity are also observable with advancing age. In particular, fine-motor dexterity appears to be most affected by the aging process, gradually impacting the use of fingers and hands during tasks that require pinching, grasping or the manipulation of objects, finger strength, or the coordinated use of the fingers and hands [38]. Similarly, gray and white matter deterioration is observable after the fifth decade of life [39,40]. Among sighted print readers, a correlation exists between degree of hippocampal shrinkage, performance on memory-based tasks (such as word retention) and overall memory decline [40]. Though the relationship between working-memory and braille reading performance has not been directly explored, it has been shown that age-related declines in short-term working memory are significantly correlated with reading comprehension difficulties among the sighted [41].

Although increased age is generally correlated with declines in tactile, motor and cognitive capacities, these characteristics have been measured using a wide range of instruments [42,43]. Moreover, tactile perception, motor dexterity and cognitive functioning are broad descriptors of capacities that may refer to different underlying components that are not directly comparable [44]. These considerations may therefore give rise to inconsistencies among results, depending on the specific capacity that is being assessed and the measurement instrument that is used. For example, tactile sensation can be passively perceived (without any movement between the stimulus and the skin) or actively perceived (where there is movement or friction between the stimulus and the skin), each of which activate different receptors [43,44]. The passive 2-point discrimination test, originally pioneered by E.H. Weber in the mid-nineteenth century [45], is routinely employed within medical and research domains but has been called into question due to its purportedly poor test-retest reliability. Alternative measurements of passive tactile acuity (such as the Grading Orientation Test) which emphasize the ability to discern groove orientation rather than the ability to perceive two individual points have therefore also been devised [43]. Quite apart from the specific instrument used to measure different facets of tactile acuity, the question of whether methods used to measure passive and active touch acuity are interchangeable remains the subject of debate [25,43,46]. Reliance on the findings of a single study or the use of a specific instrument may therefore lead to uninformed clinical decisions, such as wrongly assuming that performance on a specific measure will predict braille reading capacity.

While congenital visual impairments were historically prevalent [4,47], there has been a steady increase of working-age and older adults with acquired visual impairment over recent decades. It is projected that the prevalence of age-related visual impairment will double in Canada and triple worldwide over the next two decades, due to both population growth and aging [15]. This raises critical new questions for rehabilitation practitioners, including the need to understand how older populations and those who learn braille later in life differ from children in underlying mechanisms that influence their braille training outcomes, and whether specific remedial activities or supports would enhance their braille reading performance. For example, a report on braille and aging compiled by Cryer [17] synthesized several existing methods used to test and train tactile ability among adult braille clients. Though vital in that it answered some initial questions, this report did not include a systematic overview of all existing primary literature and did not consider the contribution of motor

and cognitive capacities within the braille reading context. Recognizing this, the authors concluded by explicitly emphasizing the need to explore these themes in greater depth as a first step towards developing methods to better support older adults who learn braille [17].

The aims of this review are to (1) identify and describe existing literature on the relationship between tactile, motor and cognitive capacities and braille reading performance; (2) summarize the range of instruments that have been used to measure these capacities, and (3) describe the extent to which the relationship between age and braille reading performance is considered within these investigations. This overview will clarify the current state of knowledge on braille and aging within a field that has traditionally focused almost exclusively on braille learning in childhood [5,48], and will set future research agendas on braille and aging by highlighting where current knowledge gaps exist.

Methods

A scoping review [49] that summarizes all relevant primary studies was deemed to be optimal, rather than alternative review methodologies that exclude articles on the basis of sample or effect size. Following the scoping review methodology outlined by Arskey and O'Malley [49] and Levac, Colquhoun and O'Brien [50], this study consisted of five separate stages, each of which is described below. This review also complies with the methodological recommendations outlined within the Joanna Briggs Institute manual for conducting systematic scoping reviews [51].

Stage 1: identifying the research questions

This scoping review is based on the following research questions:

1. What is known about the relationship between tactile, motor and cognitive capacities and braille reading performance?
2. What are the instruments that have been used to measure these capacities?
3. To what extent is the relationship between age and braille reading performance considered within these investigations?

The search strategy for this study was guided by the following parameters:

Population

This review focuses on the study of participants who read braille tactually with their fingers. Studies with braille readers who are described as blind, low vision or visually impaired are included, even if specific acuities and fields are not reported. Braille readers of any age and any braille level are included, as long as the study in question explores the relationship with at least one of the identified capacities (tactile, motor or cognitive) and at least one of the braille reading measures (reading speed, accuracy or comprehension).

Concept

- Tactile capacity: may include studies of passive acuity, where a stimulus is applied to the fingertip without any movement between the finger and the stimulus, or active (haptic) acuity, where such movement is permitted or required (as with the reading of braille) [42].
- Motor capacity: may include measures of fine or gross motor dexterity [52], as well as studies that examine the use of fingers and hands and the relationship of these patterns to braille reading outcomes [53].

- Cognitive capacity: refers to domain-specific cognitive mechanisms that are known to decline with age, such as working-memory, sustained attention and information processing [54]. Notably, this does not include level of education, phonological awareness, orthography or other literacy-based competencies. We recognize the importance of prior education and literacy experiences, but narrowed the focus of the present investigation to the physiological and cognitive capacities that are known to decline with age.
- Braille reading performance is divided into the following sub-components, in line with measures usually considered when assessing braille reading skills [2]: speed (characters or words per minute), accuracy (number of misread characters or words) and comprehension (understanding of the text, typically assessed through the use of comprehension questions or methods such as the closed procedure) [2]. Studies which examine at least one of these reading outcomes in relation to tactile, motor or cognitive capacities were included. Both oral and silent reading measures were deemed eligible as is the reading of uncontracted (alphabetic) or contracted (abbreviated) braille.
- Age: To address the final research question on the extent to which the relationship between age and braille reading performance is explored within the eligible studies, three age-related variables are considered: chronological age, age of onset, and age when braille was learned.

Context. No limitations were placed on geographic location or date of publication. Only peer-reviewed articles published in English were considered.

Stage 2: identifying relevant articles

A comprehensive search of four peer-reviewed academic databases (PsycInfo, ERIC, Cochrane and PubMed) was conducted in August 2019 and updated in July 2020, in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist: see [Supplementary Material](#) (PRISMA-ScR Checklist) for details. Given the limited size of the research base relating to braille, the decision was made to simply search for the word "braille" and to rely on the inclusion criteria to narrow the analysis (see [Table 1](#) for inclusion/exclusion criteria). Second, a manual search in the JVIB online database was conducted in July 2020, due to the relevance of this publication to the field of braille and blindness. Given the focus on braille and blindness within JVIB, specific key words were used to narrow the search: (keyword: "braille AND (speed OR accuracy OR comprehension).") Finally, the reference lists of all included articles were reviewed to ensure that no relevant articles were omitted. All relevant citations and abstracts were downloaded and imported into a Microsoft Excel worksheet. Duplicates were flagged (based on their title and author list) with a custom macro and then manually reviewed prior to being removed.

Stage 3: article selection

Articles were screened by two reviewers (the first author and an additional research assistant). Screening consisted of a two-stage process, beginning with the screening of titles and abstracts and finally with the review of the full texts of those articles which had not been excluded at the first stage. Inclusion/exclusion decisions

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
<ul style="list-style-type: none"> Studies which explore the relationship between tactile, motor and/or cognitive capacities and braille reading performance (speed, accuracy and/or comprehension), regardless of whether a relationship is found Study samples comprised of tactual braille readers irrespective of age or braille level, including blind participants and blindfolded sighted participants who learned braille entirely through touch Peer-reviewed articles published in English No restrictions placed on geographic location or date of publication Any quantitative study designs that consider a correlation between capacities and braille reading outcomes, including cross-sectional and longitudinal studies 	<ul style="list-style-type: none"> Studies which explore tactile, motor or cognitive capacities but that do not examine a correlation between these capacities and braille reading performance Studies that explore a relationship between braille reading performance and other demographic variables (education, gender, employment level, etc.) rather than tactile, motor or cognitive capacities; Studies focused specifically on the relationship between literacy skills rather than tactile, motor or cognitive capacities (such as orthography, phonetics, vocabulary) and braille reading outcomes Study samples comprised of sighted participants who read braille visually Studies that explore the relationship between tactile, motor or cognitive capacities and performance on tactile recognition tasks rather than reading performance (such as the ability to differentiate between different tactile symbols) Studies not available in English Non-peer-reviewed materials, such as opinion pieces, literature reviews, conference proceedings, books and dissertations Secondary research not reporting on primary data or findings Qualitative studies about braille that do not consider correlations

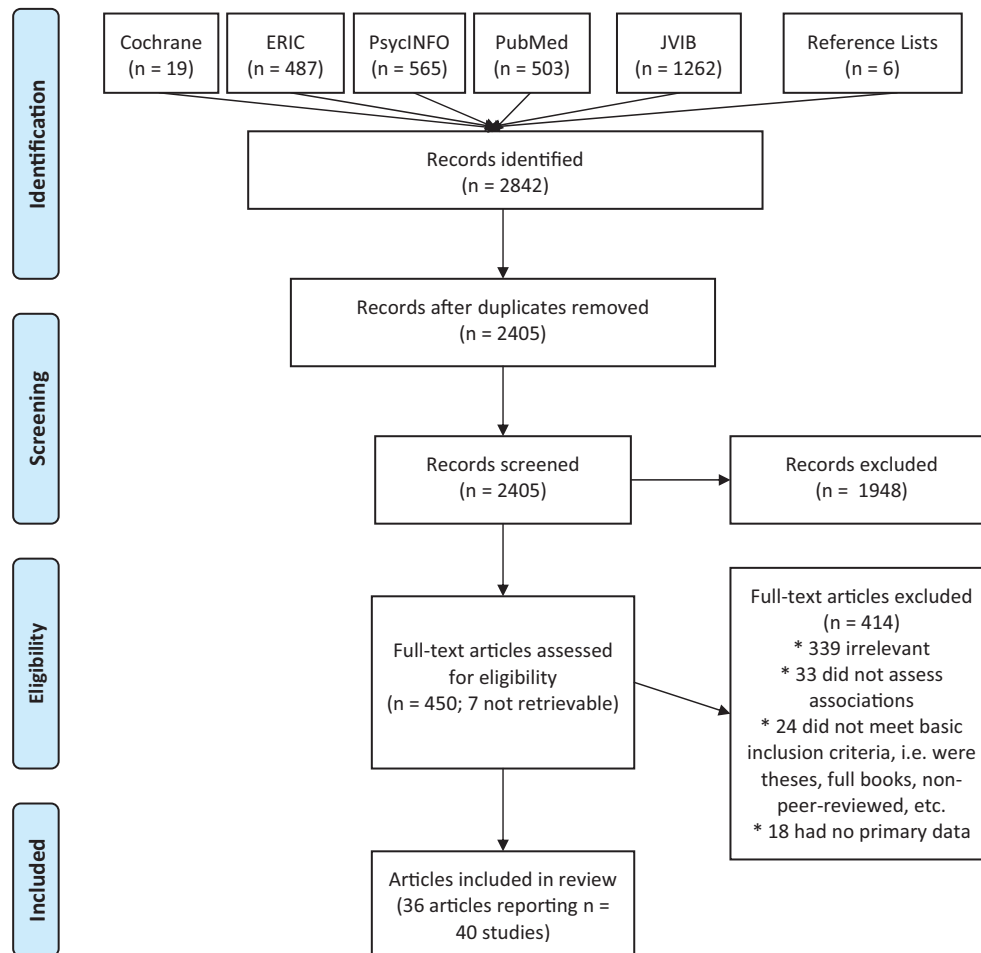


Figure 1. PRISMA-ScR diagram showing flow of included studies.

were marked in separate files by each reviewer and then compared and discussed.

Figure 1 shows the flow of article selection and number of excluded articles at each stage of the process (including results from both the initial search and the July 2020 update).

The search identified 2405 articles after duplicates were removed (including 6 additional articles identified through manual review of the reference lists of included articles). Some articles

reported on multiple studies and, where that occurred, this will be indicated.

Titles and abstracts of an initial 250 articles were reviewed by the two reviewers, with 83% agreement as to inclusion (Cohen's $kappa = 0.76$ [0.71, 0.81], $p < 0.01$). Differences were resolved between the reviewers through discussion, and after screening all 2405 titles and abstracts, 91% agreement was achieved ($kappa = 0.84$ [0.81, 0.87], $p < 0.01$). Where doubt remained about inclusion, articles were kept.

Screening of the titles and abstracts left 457 which met the criteria for a full-text review. The full text of 450 of these papers was then acquired (7 could not be obtained) and assessed against the inclusion criteria by the two reviewers, with 83.1% agreement achieved ($kappa=0.57$ [0.46, 0.68], $p<0.01$). It became evident that the most common disagreement related to articles that reported on relevant tactile, motor or cognitive capacities, but did not actually consider any of those characteristics in the analysis. With those articles removed, 93.2% agreement was achieved ($kappa=0.81$, [0.76, 0.86], $p<0.01$), and the remaining disagreements were resolved through discussion between the two reviewers, resulting in 36 articles selected for inclusion. All analyses for interrater reliability were conducted using the *irr* [55] and *psych* [56] packages from the computer program R (The R Foundation for Statistical Computing, Vienna, Austria, version 3.4.4).

Stage 4: charting the data

The 36 articles that met the inclusion criteria [8–12,27,57–86] were then subject to data extraction following the guidelines outlined by Peters et al. [51]. The extracted data for each study are summarized in Appendix.

Stage 5: collating, summarizing, and reporting the results

- A. Descriptive numerical analysis: Numerical analysis (percent-age, range, central tendency, variation) was computed to describe the nature and distribution of all included studies.
- B. Qualitative thematic analysis: Following the procedure for qualitative thematic analysis outlined by Braun et al [87], the 36 included studies were coded by the two reviewers into one of three categories according to whether they examined tactile, motor or cognitive capacities in relation to braille reading performance. The studies were further categorized into subthemes to describe the underlying tactile, motor and cognitive capacities investigated in the studies. Each reviewer

coded the articles separately and this was then compared through discussion, where no disagreements were observed.

Results

The 36 articles (representing 40 unique studies) that met the inclusion criteria were published between the years of 1934 and 2019. Figure 2 depicts the number of articles published in each decade. It can be seen that between 1954 and 1994, the number of publications steadily increased, resulting in more than half (58%) of the included studies published during this time frame. Of interest, $n=9$ articles were published between 1984 and 1994, making this the most prolific decade. As shown in Figure 3, the top three represented journals were the Journal of Visual Impairment & Blindness ($n=9$), Research in Developmental Disabilities ($n=4$), and Neuropsychologia ($n=3$). Table 2 summarizes the characteristics of the 36 articles (40 studies), and the detailed data extracted is provided in Appendix.

As will be discussed, two notable characteristics of the included studies were their sample size and the range of included participant ages (depicted in Figure 4). The sample size for the 40 studies ranges between 6 and 73 participants (with two outliers having $n=120$ and $n=256$ respectively, both focused on young children). The mean sample size among the 40 studies is 37.1 (SD = 46.8) (removing the two outliers: mean = 26.4, SD = 14.1) and only four have $n >= 50$. Collectively the studies included participants between the age of 3 and 82 (mean = 30.1, SD = 14.2); however, the average lower and upper bounds of the age groups represented (where this information was available) were 14.3 and 40.1 respectively. Among the 32 studies that reported sufficient information to determine the age range of participants, 32.5% ($n=13$) studies included participants over the age of 60, and 25% ($n=10$) included only participants below the age of 21. Importantly, 20% ($n=8$) did not provide enough information to determine the age range of participants, and a full 47.5% ($n=19$) did not report the mean or median age of participants.

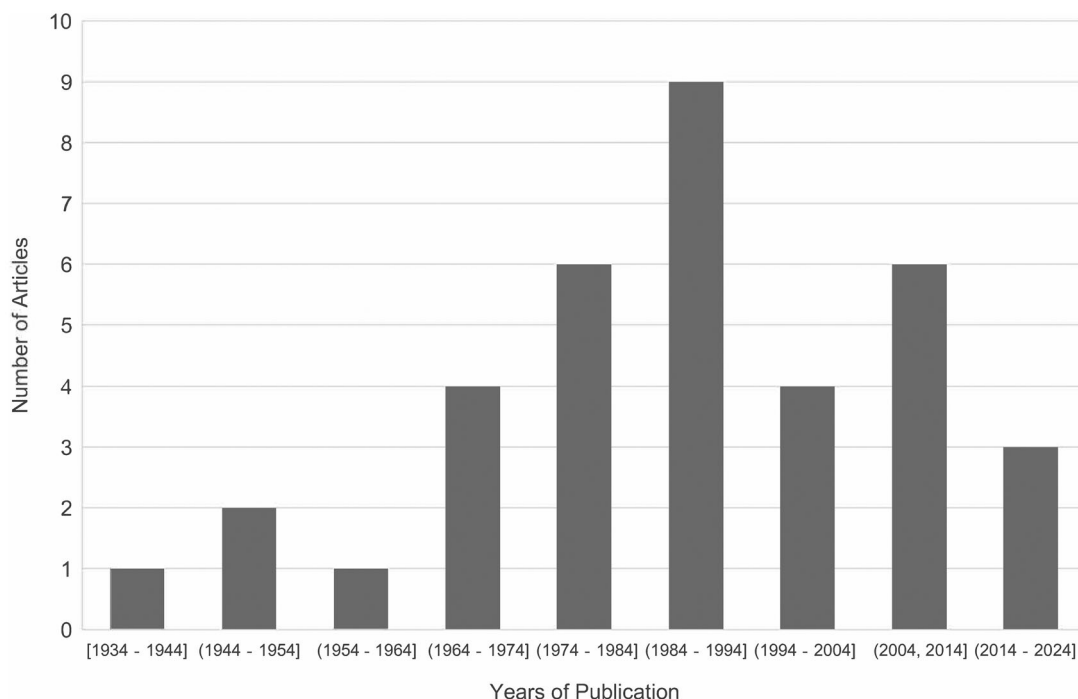


Figure 2. Histogram depicting the number of published articles appearing in each decade since 1934.

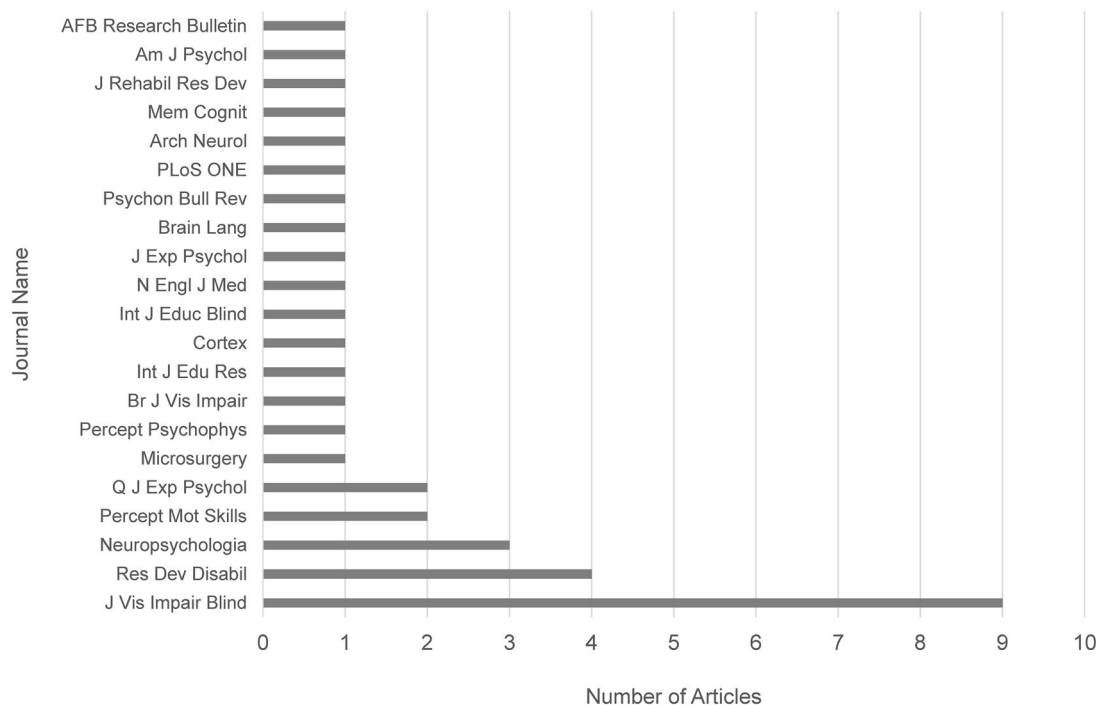


Figure 3. Graph depicting the number of articles published by journal of publication.

Table 2. Summary of characteristics of included studies.

Characteristic	N	% of Studies
Study location		
United States	20	50%
Canada	3	7.5%
Holland	3	7.5%
Japan	2	5%
Belgium	1	2.5%
China	1	2.5%
England	1	2.5%
Estonia	1	2.5%
France	1	2.5%
Greece	1	2.5%
Poland	1	2.5%
Spain	1	2.5%
Nature of investigation		
Cross-sectional	29	72.5%
Prospective	10	25%
Longitudinal	1	2.5%
Capacities explored		
Motor	25	62.5%
Tactile	15	37.5%
Cognitive	5	12.5%
Exploring multiple capacities	6	15%
Braille reading measures explored		
Speed	33	82.5%
Accuracy	14	35%
Comprehension	3	7.5%
Capacity ^a	3	7.5%
Exploring multiple measures	13	32.5%
Age groups represented in sample		
Indeterminate ^b	8	20%
Children (< 10)	11	27.5%
Youth (10 – 18)	20	50%
Adults (19 – 59)	16	40%
Older adults (60+)	13	32.5%

^aThese studies measured braille reading performance on a binary “can vs cannot read” basis, or described reading performance as “poor/fair/very good” without any further explanation as to the meaning of these descriptions.

^bInsufficient information was provided in these studies to determine the age range of participants.

Relationship between capacities, braille reading and instruments used

Tactile capacities

Among the 40 studies (36 articles), 15 studies (13 articles) explored the relationship between tactile capacity measures and braille reading performance (Table 3). Of these, 8 studies (7 articles) examined passive (or static) acuity and 7 studies (6 articles) explored active (or haptic) acuity. In total, 19 different instruments were used to measure tactile capacity (11 for passive and 8 for active). Only 6 of the instruments were used in more than one study (Grating Orientation Test, Static Two-point Discrimination Test, Two-point Gap Discrimination Test, Nylon Filament Test, Roughness Discrimination Test, and Legge Dot Chart). Overall, 12 studies (10 articles) explored the relationship between tactile capacity and reading speed, 4 studies (4 articles) for reading accuracy, and 3 of the studies (3 articles) explored the relationship between tactile capacity and a more general can read/cannot read measure. None of the articles explored the relationship between tactile capacity and reading comprehension.

Motor capacities

Twenty-five of the studies (23 articles) examined motor capacities in relation to braille reading performance, with 22 studies (20 articles) investigating reading speed, 9 studies (8 articles) examining accuracy, and 5 studies (5 articles) exploring reading comprehension (see Table 4). The measurement of motor capacities in these studies relied upon the observation of fingers and hand usage during braille reading. Among the 25 studies, 2 examine the relationship between contact force (the amount of pressure applied by the reading fingers) and braille reading performance; 5 focused on the use of specific fingers during braille reading; 9 focused on hand usage (left vs. right hand); and 13 focused on the use of specific hand reading patterns (whether the hands move together across the line or whether they employ the more

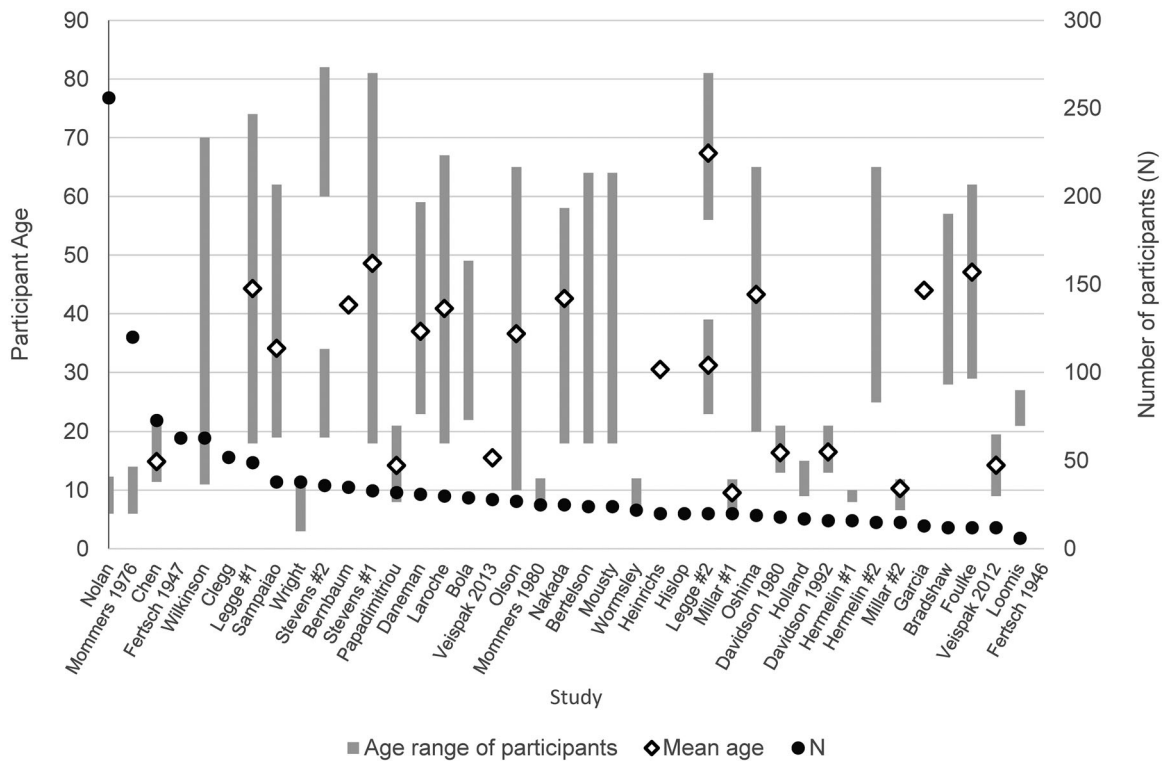


Figure 4. Graph summarizing the age range of participants (depicted by a bar plotted against the left-hand side axis) and sample size (depicted by a dot against the right-hand side axis) in each of the included studies. Diamonds indicate the mean age of participants within the sample.

advanced scissors technique, where one hand reads the remainder of the current line while the other begins reading the next line).

Cognitive capacities

In total, 5 of the studies (reported in 5 articles) explored the correlation between cognitive capacities and braille reading performance, with 5 investigating speed, 3 investigating accuracy, and 1 exploring comprehension (see Table 5). Overall, 7 instruments were used, which fall into one of three broad categories: intelligence or IQ tests; tests of processing speed (the speed at which a participant is able to process information being perceived); and tests relating to short-term working memory (the ability to retain and recall information that is just perceived).

The relationship between age and reading performance

Table 6 provides an overview of the extent to which age-related variables were considered across the 40 studies. The 11 studies (in 10 articles) which directly explored the relationship between age-related variables (chronological age, age of onset or braille learning age) and braille reading performance included between 13 and 73 participants (mean 31.9, SD 16.8) ranging in age from 11 to 74 (mean 36.9, SD 9.5).

Overall, 5 of the studies (in 5 articles) explored the relationship between chronological age and braille reading performance, with 4 examining reading speed; 0 exploring reading accuracy; 2 for reading comprehension, and 1 exploring general braille reading capacity.

In total, 5 of the studies (in 5 articles) explored the relationship between age of onset and braille reading performance. All 5 explored the relationship between age of onset and reading speed; 1 also explored reading accuracy; and 2 also explored reading comprehension. It is impossible to provide a lower and

upper age of onset range for these studies collectively, as sufficient information is not provided and different definitions of “age of onset” are used across these studies. While some articles provided continuous age of onset values, others simply categorized participants into dichotomous groups (e.g., congenital vs. adventitious). The specific definitions used for age of onset for these studies are indicated in the legend found at the end of Table 6.

In total, 3 of the studies explored the relationship between the age at which braille was learned and braille reading performance. Of these, 2 examined braille learning age and reading speed; 1 examined reading accuracy; 2 explored the relationship with reading comprehension, and 1 explored the relationship between braille learning age and general “braille reading capacity.” Note that the definition of braille learning age varied across these 3 studies. Garcia [67] did not specifically identify the age at which participants learned braille (except to note that participants had between 1 and 55 years reading experience); Laroche [72] divided participants into two groups (learned *before* age 10 and learned *after* age 10); and in Nakada [78], participants had completed two years of braille rehabilitation training yielding braille learning ages of between 18 and 58 (mean 42.6, SD 10.2).

Discussion

The aim of this scoping review was to summarize the breadth and nature of research exploring the relationship between tactile, motor and cognitive capacities and braille reading performance, the instruments used to measure these capacities, and the extent to which age has been considered within these investigations. Spanning 4 databases and 85 years of published literature, this review is noteworthy not merely for the insights it affords, but also for heightening the discrepancies that remain. Though no

Table 3. Tactile capacities and relationship to braille reading performance.

Instrument	Speed	Accuracy	Capacity
Passive tests			
Distinguishing between two points at various distances			
Two-Point Discrimination Test (Static)	$N = 1$ Not sig = 1: [10] (Study #1)		$N = 2$ Sig = 1: [78]* Not Sig = 1: [27]◆
Two-Point Discrimination Test (Moving)			$N = 1$ Sig = 1: [78]*
Identification of the presence/absence of a gap			
Disk Gap Detection	$N = 1$ Sig = 1: [10]* (Study #1)		
Two-Point Gap Discrimination Test	$N = 1$ Sig = 1: [10]* (Study #2)		$N = 1$ Sig = 1: [68]◆
Identification of the orientation of a stimuli on the finger			
Grating Orientation Test	$N = 3$ Not sig = 1: [11] Sig = 2: [83]*; [12]*	$N = 2$ Not sig = 2: [83], [12]	
Line Orientation	$N = 1$ Not sig = 1: [10] (Study #2)		
Two-Point Orientation Test	$N = 1$ Sig = 1: [10]* (Study #2)		
Differentiating the length of stimuli			
Length Discrimination	$N = 1$ Not sig = 1: [10] (Study #2)		
Identifying the sensation of touch or vibration			
Nylon Filament Test			$N = 2$ Sig = 1: [68]◆ Not sig = 1: [78]
Vibro-Tactile Detection			$N = 1$ Sig = 1: [68]◆
Measurement of electrical impulses transmitted through the nerve			
Nerve Conduction Study			$N = 1$ Not sig = 1: [27]◆
Active Tests			
Differentiating and categorizing based on size/shape/texture			
Haptic Figure Orientation Test	$N = 1$ Not sig = 1: [75]◆		
Haptic Object Discrimination Test	$N = 1$ Not sig = 1: [75]◆		
Haptic Size Discrimination Test	$N = 1$ Not sig = 1: [75]◆		
Roughness Discrimination Test	$N = 2$ Sig = 1: [8]* Not sig = 1: [76]◆	$N = 1$ Sig = 1: [8]*	
Tactual Discrimination Test	$N = 1$ Sig = 1: [60]*	$N = 1$ Sig = 1: [60]*	
Tactile Kinesthetic Form Discrimination Test	$N = 1$ Not sig = 1: [75]◆		
Determining orientation of tactile figures (logarithmically decreasing size)			
Legge "Dot Chart"	$N = 2$ Not sig = 2: [9] (Study #1); [80]		
Legge "Ring Chart"	$N = 1$ Not sig = 1: [9] (Study #2)		

*Study found a reportedly significant relationship between the assessment and the identified reading performance metric (typically at the 0.05 level). ◆ Study described the results as being "significant" but did not report statistical significance tests or results. ◆ Study did not report statistical significance tests or results, and did not describe the results as being "significant."

restrictions were placed on year of publication, only 36 articles (representing 40 studies) published between 1934 and 2019 were deemed eligible. Of note, although braille reading draws on multiple capacities [1], none of the included studies explore the relationship between tactile, motor and cognitive capacities and braille reading measures within a single sample. This may lead to an over-simplification of the braille reading process, and the misinterpretation of findings which obscure the potential influence of other confounding age-related variables. Similarly, though a wide range of instruments has been used to measure these capacities, most of these tools have only been employed within a single study, highlighting the need for replication. As the prevalence of age-related visual impairment continues to increase, there is an evident need for research focusing on older adults and on those who learn braille beyond childhood.

Relationship between capacities and braille reading and the range of instruments used

Tactile capacities

It can be seen that among the 15 studies (13 articles) in Table 3, there is a clear focus on whether passive acuity measures could be used to predict current or future braille reading capacity. This trend persists across the decades, with the earliest passive tactile acuity study published in 1969 and the most recent in 2016.

The interest in passive acuity originates from the medical domain where such tools are routinely employed to assess neurological damage, including diabetic neuropathy of the fingertips [43]. From a clinical perspective, several authors have also highlighted that passive acuity instruments are often portable and simple to administer [17]. In the static two-point discrimination

Table 4. Motor capacities and relationship to braille reading performance.

Capacity	Speed	Accuracy	Comprehension
Contact force (pressure)	<i>N</i> = 1 Not sig = 1: [71]	<i>N</i> = 1 Not sig = 1: [73]◆	
Hand movement patterns	<i>N</i> = 11 Sig = 10: [72]*, [59]*, [63]*, [64]◆, [67]*, [74] (Study #2)*, [77]*, [85]◆, [86]*, [88]* Not sig = 1: [70]◆	<i>N</i> = 2 Sig = 1: [81]* Not sig = 1: [62]◆	<i>N</i> = 4 Not sig = 4: [59,62,72]◆, [67]
Hand used (left/right)	<i>N</i> = 10 Sig = 7: [65]*, [69]* (Study #1 and #2), [74]* (Study #1), [76]*, [82]*, [84]* Not sig = 3: [58], [66], [77]	<i>N</i> = 6 Sig = 3: [69]* (Study #1 and #2), [84]* Not sig = 3: [58,66,74] (Study #1)	<i>N</i> = 1 Not sig = 1: [84]
Finger(s) used	<i>N</i> = 5 Sig = 3: [66]*, [69]* (Study #1), [79]* Not sig = 2: [76], [84]	<i>N</i> = 3 Sig = 2: [66]*, [69]* (Study #1) Not sig = 1: [84]	<i>N</i> = 1 Not sig = 1: [84]

*Study found a reportedly significant relationship between the assessment and the identified reading performance metric (typically at the 0.05 level). ◆ Study described the results as being “significant” but did not report statistical significance tests or results. ♦ Study did not report statistical significance tests or results, and did not describe the results as being “significant.”

Table 5. Cognitive capacities and relationship to braille reading performance.

Capacity	Speed	Accuracy	Comprehension
Intelligence			
IQ	<i>N</i> = 2 Not sig = 2: [8]◆, [85]	<i>N</i> = 1 Not sig = 1: [8]◆	
Processing speed			
Rapid automatic naming	<i>N</i> = 2 Sig = 2: [12]*, [83]*	<i>N</i> = 2 Sig = 1: [83]* Not sig = 1 : [12]	
Short-term working memory			
Braille span test	<i>N</i> = 1 Not sig = 1: [61]		<i>N</i> = 1 Sig = 1: [61]*
Listening span	<i>N</i> = 1 Not sig = 1: [61]		<i>N</i> = 1 Sig = 1: [61]*
Listening comprehension test	<i>N</i> = 1 Not sig = 1: [61]		<i>N</i> = 1 Sig = 1: [61]*
Speech-in-noise test	<i>N</i> = 2 Not sig = 2: [12], [83]	<i>N</i> = 2 Sig = 2: [12]*, [83]*	
Verbal short-term memory tests (digit span, non-word repetition)	<i>N</i> = 3 Not sig = 3: [12], [61], [83]	<i>N</i> = 2 Sig = 2: [12]*, [83]*	<i>N</i> = 1 Sig = 1: [61]*

*Study found a reportedly significant relationship between the assessment and the identified reading performance metric (typically at the 0.05 level). ◆ Study described the results as being “significant” but did not report statistical significance tests or results. ♦ Study did not report statistical significance tests or results, and did not describe the results as being “significant.”

Table 6. Relationship between various measures of age and measures of braille reading performance (speed, accuracy, comprehension).

Measure of age	Speed	Accuracy	Comprehension	Capacity
Chronological age	<i>N</i> = 4 Sig = 1: [61]* Not sig = 3: [9]◆, [11], [79]		<i>N</i> = 2 Sig = 1: [79]◆ Not sig = 1: [61]	<i>N</i> = 1 Sig = 1: [78]*
Age of onset of blindness	<i>N</i> = 5 Sig = 4: [80]*, [61]*■, [77]*, [82]*■ Not sig = 1: [59]■	<i>N</i> = 1 Not sig = 1: [80]	<i>N</i> = 2 Not sig = 2: [59]■, [61]■	
Age braille first learned	<i>N</i> = 2 Sig = 2: [72]*, [67]*	<i>N</i> = 1 Sig = 1: [72]* (when reading aloud)	<i>N</i> = 2 Not sig = 2: [72]◆, [67]	<i>N</i> = 1 Sig = 1: [78]*

*Study found a statistically significant relationship between the factor and the identified reading performance metric. ◆ Study described the results as being “significant” but did not report statistical significance tests or results. ♦ Study did not report detailed statistical significance test results. ■ Study distinguished only between individuals with “adventitious” or “congenital” vision loss.

■ Categorical definitions for age of onset: Chen [59]: Congenital (0–10 months), Adventitious: 1–13 years; Daneman [61]: Congenital (at birth), Adventitious: “early childhood to middle adulthood”; Mousty [77]: Congenital (at birth), Adventitious: after birth (60% before age 6, 20% before age 10, 13% before age 11, 7% before age 19); Oshima [80]: Early onset (0 to 3), Late onset: 6–52; Sampaio [82]: Birth (0), Early childhood: 1.5–6.

test, for example, the points of the calipers are applied to the pad of the stationary finger at different distances from each other, in order to determine the minimal distance at which the participant is able to distinguish the presence of one or two points [10]. Given that the center-to-center distance between dots in the standard braille cell is approximately 2.28 mm [9], it is unsurprising that researchers would contemplate whether 2-point

threshold measures could be used to predict braille reading ability or whether individuals with a 2-point threshold above 2.28 mm would find it difficult to read standard braille [27,68,78].

Despite these considerations, the studies in this review differ drastically in the extent to which a relationship between passive acuity and braille reading performance is reported. Among the two most commonly used passive acuity tests within this review

(two-point and Grating Orientation), two-point is only related to braille reading performance in 1 of 3 studies, and Grating Orientation in 2 of the 3 studies. These inconsistent findings partially stem from the fact that although the Grating Orientation Test has been found to be a reliable measure of passive tactile perception [42], the two-point discrimination test depends heavily on the examiner's ability to maintain consistent force with both points across all trials, and is associated with poor test-retest reliability [42,89]. Importantly, it is also difficult to draw specific comparisons across these passive acuity studies, as sufficient demographic information (such as previous braille experience) is not always available, and 3 of the passive acuity studies simply evaluate braille reading performance using a subjective, qualitative scale (cannot read/can read with difficulty/can read well) without specific information about reading rate, accuracy or comprehension [27,68,78].

Several authors have also highlighted that passive acuity measures reveal little about activities that draw on active tactile perception [17], leading to an interest in active acuity measures. Indeed, the focus on passive acuity seems counterintuitive given that braille reading is impaired when the fingers remain static or when ineffective movements (such as vertical scrubbing) are employed [2,53,90]. Braille reading activates the nerve endings of sensory receptors, but also the muscles, joints and tendons of the fingers, hands, wrists, arms and shoulders [2,44,53]. Moreover, active tactile perception provides greater control to the participant over the stimulus being perceived and enables the use of strategies to move across symbols more effectively [9,17].

While there is no doubt that proficient braille reading requires the ability to actively perceive tactile symbols, there are 8 different active acuity instruments used across the studies in this review and only two (Roughness Discrimination Test and Legge Dot Chart) are used in more than one study. Of interest, the Legge Dot Chart is a tactile analogue to the Snellen chart used to measure the threshold of visual perception among the sighted, but is not related to braille reading speed in either of the two studies where it is used [9,80]. This tactile chart consists of nine lines of four randomly presented braille-like symbols (corresponding to the letters d, f, h, and j) where the distance between the dots in each symbol decreases logarithmically from one line to the next. Though it can be seen that blind subjects outperformed sighted age-matched subjects in Legge's study [9], no relationship between active acuity threshold and braille reading speed (using a braille version of the MN Read) is reported. Of relevance is that the blind participants in this study were all experienced braille readers with early blindness and with active acuity thresholds well below the 2.28 mm distance required for braille reading [9]. As with visual reading, it may be that further increases in acuity do not accord any additional advantage to reading speed when the acuity is already below the threshold required for successful reading [9]. It is possible that a more significant relationship between speed and acuity measures might be observed among late blind participants and among those whose tactile acuities are closer to the 2.28 mm braille threshold.

Motor capacities

A majority of the studies in this review are devoted to the motor capacities recruited during braille reading, with 25 studies (22 articles) falling within this domain (see Table 4). Of interest, this research focuses heavily on observations of finger and hand usage during braille reading, rather than on underlying measures of fine or gross motor capacities that may decline with age.

Several of the earliest studies examined whether the use of specific fingers correlate with better braille reading outcomes, and confirm the superiority of the index fingers for tactile perception [43]. Foulke [66] tested braille reading speed on 8 separate fingers for each participant (all but the two thumbs) and found that performance was best on the index fingers of both hands. This is unsurprising given that the index fingers contain the greatest density of sensory receptors (much like the fovea of the eye) and the number of these receptors gradually declines with each digit [44]. While the superiority of the index fingers for tactile perception is undisputed, it is now also recognized that multiple fingers are often recruited during the braille reading process [2]. Even if the index fingers are the most dominant, students are often encouraged to perceive the braille reading line with multiple fingers as this can facilitate reading by confirming what is being processed [2,76]. From an aging perspective, it is possible that readers with damage or disease in the index fingers may develop a preference for relying more heavily on alternative fingers during braille reading and especially benefit from the use of multiple fingers where tactile perception is impaired, contributing to cortical magnification in the preferred reading fingers [27,44]. As such, studies that test braille reading without taking into account preferred reading fingers and habits may not provide a realistic measure of reading performance in such cases.

Much of the motor literature focuses heavily on hand dominance and hand reading patterns, and the question of whether the left or right hand is best for braille reading. Several studies from the 1970s and 1980s are premised on evidence suggesting that sighted participants who are unfamiliar with braille recruit the right hemisphere during braille reading (believed to be responsible for spatial processing) and will therefore perform best when using the left hand. Alternatively, it was believed that experienced braille readers show a right hand dominance because they recognize braille symbols for their linguistic properties and in turn reveal a left hemispheric superiority [58,69,82]. Despite the appeal of arguments based on cortical asymmetry, these studies result in inconsistent findings and confirmed that there is no universally best hand for braille reading. Instead, multiple parts of the cortex (including the occipital cortex) are recruited during the braille reading process, and two-handed reading is associated with faster reading rates [53].

A total of 13 studies in this review explore the influence of specific hand reading patterns. These patterns are typically categorized as one-handed reading, where either the left or right hand is used alone; two-handed reading where both hands move together with the index fingers spaced slightly apart from each other; and disjointed reading whereby the two hands read together until the midpoint, after which the right hand reads the remainder of the line while the left hand moves diagonally to locate the start of the following line [1]. The latter pattern is virtually always associated with the fastest reading rates, owing in part to the time saved in transitioning from one line to the next [57]. There is considerable evidence that when two hands are used collaboratively, each hand is independently contributing to the reading process. Mommers, for example, observed that when both hands are used, the left hand is used to confirm what has just been read with the right, and in some cases even regresses to re-read passages for confirmation while the right hand continues reading ahead [76]. It has likewise been observed that where large disparities exist between the performance of the left and right hand individually for a particular subject, this disparity limits the potential two-handed reading performance [77].

While two-handed reading is associated with faster reading rates, Wormsley [53] underscores that even where readers use advanced two-handed reading techniques, reading rates do not necessarily improve where tactile recognition skills are deficient [53]. Indeed, poor tactile perception may adversely affect hand reading strategies [71]. These considerations raise the limitations of studies that examine motor capacities in isolation from other factors (such as tactile perception) that may influence overall braille reading rates. Of interest is that, in this review, only the study by Mommers [75] included both measures of tactile perception and motor capacities within the same sample.

Finally, it is well established that motor dexterity, and particularly fine motor skills, declines as a result of the normal aging process and may carry additional consequences that should be considered within the training context [26,38,90]. Though manual dexterity training has led to performance gains among older sighted adults, the degree to which such gains are possible appears to depend on the complexity of the task [38]. Importantly, none of the studies in this review measure fine motor dexterity or whether age-related changes may influence the hand movements which support braille reading.

Cognitive capacities

In total, 5 of the articles (representing 5 studies) in this review directly explore the relationship between cognitive capacities and braille reading performance (see Table 5). Most of these studies explore the influence of short-term working memory on braille reading outcomes, with a total of 4 studies falling within this domain. Despite an evident relationship between working memory and aspects of braille reading performance, the studies in this review employ a wide range of working memory instruments including those which require the completion of auditory or braille reading span tasks, but none specifically evaluated tactile short-term working memory. While this is not inconsistent with research on sighted readers (where measures of listening comprehension have been shown to be associated with reading comprehension ability, for example [61]), care must be taken when using such measures to ensure that other impairments (such as undiagnosed hearing loss) are not confounding results. Furthermore, assessing braille reading performance against a task which itself requires the reading of braille (in the case of “braille span” measures [61], for example) will potentially disadvantage those with poor braille skills who may read slower and who experience greater cognitive load during reading. Instruments such as the one described in Papagno et al. [91] may be worth further exploration as a method for better isolating tactile short-term working memory performance from the potential influence of reading ability.

Prior research also highlights the need to assess comprehension independently of short-term working memory. Of interest, these cognitive aspects are not considered within the studies of this review, save for Daneman [61] where a comprehension monitoring exercise was proposed to permit assessment of comprehension even in the presence of degraded short-term working memory. These factors are important to control in future research particularly given that cognitive processing errors common among older adults may be masked by apparent poor performance on other measures (such as tactile acuity assessments) [92].

Consideration of age

It is apparent that, although the studies in this review examine different aspects of braille reading performance, this research

focuses heavily on younger readers and on those who learn braille early in childhood. Of the 40 studies, only 13 include participants who are above the age of 60, most of whom learned braille early in life. Moreover, where braille learning age is directly explored in relation to reading performance measures, insufficient information is often available. For example, Laroche [72] merely divides participants between those who learn before and after the age of 10. This limits the degree to which results can be meaningfully interpreted, given that the abilities of adults differ drastically from those in older adulthood who experience greater age-related declines [3]. Though it is understood that the typical aging process contributes to declines in tactile, motor and cognitive capacities [3], evidence also indicates that individuals with extensive tactile exposure and practice maintain tactile perception abilities as they age [9]. For these reasons, the chronological age of participants should not be examined in isolation from their braille learning age or frequency of braille usage. Despite these considerations, none of the studies in this review consider these age-related variables in unison.

Limitation and weaknesses of this study

This is the first study to synthesize primary research on the relationship between physiological and cognitive capacities and braille reading performance. It is possible that some relevant articles have been omitted if the titles and abstracts did not clearly map onto the inclusion criteria. We limited our search to four academic databases, and on peer-reviewed articles published in English. Nonetheless, we conducted a manual search through the Journal of Visual Impairment and Blindness and through the reference lists of all included articles, and placed no restrictions on date of publication.

Second, as with other scoping reviews, this overview does not aggregate research findings nor eliminate studies on the basis of quality, sample size and effect size. Given the low prevalence of blindness which often contributes to smaller sample sizes, it was believed that a meta-analysis would significantly restrict the scope of research considered. Future studies are needed to build upon this knowledge base and to assess the reliability of specific measurement instruments.

Third, we restricted this review to the physiological and cognitive capacities known to decline with age. Importantly, we did not consider external factors which may further influence the braille learning experience. Research points to a persistent shortage of specialized teachers who serve blind children, and access to rehabilitation services for adults may be constrained by geographic location, funding programs and restrictive eligibility criteria [18]. Future research is needed to explore the facilitators and barriers encountered by adults and seniors who pursue braille training, in order to understand the influence of external factors on the adult braille learning process.

Conclusion

Collectively, the studies in this review underscore the importance of developing tactile perception and efficient hand reading strategies throughout the learning process. However, they do not directly explore the potential influence of age-related declines in fine-motor and short-term working memory. Moreover, this research focuses heavily on younger participants and on individuals who learned braille early in life. As rehabilitation practitioners encounter a growing number of older adults with acquired visual impairments, it will be vital to understand how the aging process

may uniquely shape their braille learning experiences. This context would highlight where areas of difficulties may exist, and what specific remedial activities will help to support the success of older clients who are served.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article. Readers interested in accessing our selected articles for specific purposes related to their respective research are invited to do so by contacting the corresponding author through the provided email address.

References

- [1] Kusajima T. Visual reading and braille reading: an experimental investigation of the physiology and psychology of visual and tactual reading. New York (NY): American Foundation of the Blind; 1974.
- [2] Wormsley DP, D'Andrea FM. Instructional strategies for braille literacy. New York (NY): American Foundation for the Blind; 1997.
- [3] Kandel ER, Schwartz JH, Jessell TM, et al. Principles of neural science. New York (NY): McGraw Hill; 2013.
- [4] Holbrook MC, McCarthy T, Kamei-Hannan C. Foundations of education: volume I: history and theory of teaching children and youths with visual impairments. 3rd ed. New York (NY): AFB Press; 2017.
- [5] Ferrell KA, Mason L, Young J, et al. Forty years of literacy research in blindness and visual impairment. Greeley (CO): University of Northern Colorado; 2006.
- [6] Steinman BA, LeJeune B, Kimbrough B. Developmental stages of reading processes in children who are blind and sighted. *J Vis Impair Blind*. 2006;100:36–46.
- [7] Goldreich D, Kanics IM. Performance of blind and sighted humans on a tactile grating detection task. *Percept Psychophys*. 2006;68:1363–1371.
- [8] Nolan CY, Morris JE. Development and validation of the Roughness Discrimination Test. *Int J Educ Blind*. 1965;15:1–6.
- [9] Legge GE, Madison CM, Vaughn BN, et al. Retention of high tactile acuity throughout the life span in blindness. *Percept Psychophys*. 2008;70:1471–1488.
- [10] Stevens JC, Foulke E, Patterson MQ. Tactile acuity, aging, and braille reading in long-term blindness. *J Exp Psychol Appl*. 1996;2:91–106.
- [11] Bola L, Siuda-Krzywicka K, Paplinska M, et al. Braille in the sighted: teaching tactile reading to sighted adults. *PLoS One*. 2016;11:e0153394.
- [12] Veispak A, Boets B, Ghesquière P. Differential cognitive and perceptual correlates of print reading versus braille reading. *Res Dev Disabil*. 2013;34:372–385.
- [13] Veispak A, Boets B, Ghesquière P. Parallel versus sequential processing in print and braille reading. *Res Dev Disabil*. 2012;33:2153–2163.
- [14] Van Boven RW, Johnson KO. The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger. *Neurology*. 1994;44:2361–2361.
- [15] Varma R, Vajaranant T, Burkemper B. Visual impairment and blindness in adults in the United States: Demographic and geographic variations from 2015 to 2050. *J Am Med Assoc Ophthalmol*. 2016;134:802–809.
- [16] Cruess AF, Gordon KD, Bellan L, et al. The cost of vision loss in Canada. 2. Results. *Can J Ophthalmol*. 2011;46:315–318.
- [17] Cryer H, Home S. Final report: feasibility of developing a diagnostic touch test to determine braille reading potential. Birmingham (UK): RNIB Centre for Accessible Information; 2011.
- [18] Ponchillia PE, Durant PA. Teaching behaviors and attitudes of braille instructors in adult rehabilitation centers. *J Vis Impair Blind*. 1995;89:432–439.
- [19] Ponchillia PE, Ponchillia SV. Foundations of rehabilitation teaching with persons who are blind or visually impaired. New York (NY): American Foundation for the Blind; 1996.
- [20] Schroeder FK. Perceptions of braille usage by legally blind adults. *J Vis Impair Blind*. 1996;90:210–218.
- [21] Rubin GS. Measuring reading performance. *Vision Res*. 2013;90:43–51.
- [22] Brown JC, Goldstein JE, Chan TL, et al. Characterizing functional complaints in patients seeking outpatient low-vision services in the United States. *Ophthalmology*. 2014;121:1655–1662.
- [23] Rex E, Koenig A, Wormsley D, et al. Foundations of braille literacy. New York (NY): American Foundation for the Blind; 1995.
- [24] Ozioko O, Hersh MA, editors. Development of a portable two-way communication and information device for deaf-blind people. Proceedings of the 13th AAATE Conference; 2015 Sep 9–12; Budapest, Hungary; 2015.
- [25] Heller KW, D'Andrea FM, Forney PE. Determining reading and writing media for individuals with visual and physical impairments. *J Vis Impair Blind*. 1998;92:162–175.
- [26] Hughes B. Movement kinematics of the braille-reading finger. *J Vis Impair Blind*. 2011;105:370–381.
- [27] Bernbaum M, Albert SG, McGarry JD. Diabetic neuropathy and braille ability. *Arch Neurol*. 1989;46:1179–1181.
- [28] Hall AD, Newman SE. Braille learning: relative importance of seven variables. *Appl Cognit Psychol*. 1987;1:133–141.

- [29] Hannan CK. Review of research: neuroscience and the impact of brain plasticity on braille reading. *J Vis Impair Blind*. 2006;100:397–413.
- [30] Knowlton M, Wetzel R. Braille reading rates as a function of reading tasks. *J Vis Impair Blind*. 1996;90:227–236.
- [31] Nolan CY, Kederis JC. Perceptual factors in braille word recognition (research series no. 20). New York (NY): American Foundation for the Blind; 1969.
- [32] Bopp KL, Verhaeghen P. Aging and verbal memory span: a meta-analysis. *J Gerontol B Psychol Sci Soc Sci*. 2005;60: P223–P233.
- [33] Millar S. Perceptual and task factors in fluent braille. *Perception*. 1987;16:521–536.
- [34] Argyropoulos V, Papadimitriou V. Braille reading accuracy of students who are visually impaired: the effects of gender, age at vision loss, and level of education. *J Vis Impair Blind*. 2015;109:107–118.
- [35] Simón C, Huertas JC. How blind readers perceive and gather information written in braille. *J Vis Impair Blind*. 1998;92:322–330.
- [36] Stevens JC. Aging and spatial acuity of touch. *J Gerontol*. 1992;47:P35–40.
- [37] Goldreich D, Kanics IM. Tactile acuity is enhanced in blindness. *J Neurosci*. 2003;Apr 15:23:3439–3445.
- [38] Voelcker-Rehage C. Motor-skill learning in older adults – a review of studies on age-related differences. *Eur Rev Aging Phys Act*. 2008;5:5–16.
- [39] Gunning-Dixon F, Brickman AM, Cheng JC, et al. Aging of cerebral white matter: a review of MRI findings. *Int J Geriatr Psychiatry*. 2009;24:109–117.
- [40] Persson J, Pudas S, Lind J, et al. Longitudinal structure-function correlates in elderly reveal MTL dysfunction with cognitive decline. *Cereb Cortex*. 2012;22:2297–2304.
- [41] Siegel L. Working memory and reading: a life-span perspective. *Int J Behav Dev*. 1994;17:109–124.
- [42] Bruns P, Camargo CJ, Campanella H, et al. Tactile acuity charts: a reliable measure of spatial acuity. *PLoS One*. 2014; 9:e87384.
- [43] Foulke E. Reading braille. In: Schiff W, Foulke E, editors. *Tactual perception: a sourcebook*. New York (NY): Cambridge University Press; 1982. p. 168–208.
- [44] Heller MA, Gentaz E. *Psychology of touch and blindness*. New York (NY): Psychology Press; 2013.
- [45] Weber EH. *Weber on the tactile senses*. 2nd ed. Erlbaum (UK): Taylor & Francis, Publ; 1996. (Ross HE, Murray DJ, editors).
- [46] Schwartz AS, Perey AJ, Azulay A. Further analysis of active and passive touch in pattern discrimination. *Bull Psychon Soc*. 1975;6:7–9.
- [47] Corn AL, Lusk KE. Perspectives on Low Vision (Chapter 1). In: Corn AL, Erin JN, editors. *Foundations of low vision: clinical and functional perspectives*. New York (NY): American Foundation for the Blind; 2010. p. 3–34.
- [48] Dixon J, editor. *Braille into the next millennium*. Washington (DC): National Library Service for the Blind and Physically Handicapped; 2000.
- [49] Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res*. 2005;8:19–32.
- [50] Levac D, Colquhoun H, O'Brien KK. Scoping studies: advancing the methodology. *Implement Sci*. 2010;5:69.
- [51] Peters MD, Godfrey CM, Khalil H, et al. Guidance for conducting systematic scoping reviews. *Int J Evid Based Healthc*. 2015;13:141–146.
- [52] Tiffin J, Asher EJ. The Purdue pegboard; norms and studies of reliability and validity. *J Appl Psychol*. 1948;32:234–247.
- [53] Wormsley DP. Hand movement training in braille reading. *J Vis Impair Blind*. 1981;75:327–331.
- [54] Murman DL. The impact of age on cognition. *Semin Hear*. 2015;36:111–121.
- [55] Gamer M, Lemon J, Fellows I, et al. Package 'irr': various coefficients of interrater reliability and agreement (version 0.84). 2012.
- [56] Revelle W. Package 'psych': procedures for psychological, psychometric, and personality research (version 1.7.8). 2017.
- [57] Bertelson P, Mousty P, D'Alimonte G. A study of braille reading: 2. Patterns of hand activity in one-handed and two-handed reading. *Q J Exp Psychol A*. 1985;37:235–256.
- [58] Bradshaw JL, Nettleton NC, Spehr K. Braille reading and left and right hemisphere. *Neuropsychologia*. 1982;20:493–500.
- [59] Chen X, Liang L, Lu M, et al. The effects of reading mode and braille reading patterns on braille reading speed and comprehension: A study of students with visual impairments in China. *Res Dev Disabil*. 2019;91:103424.
- [60] Clegg GD. A study of the Tactual Discrimination Test for measuring tactual ability of the visually handicapped. Research Bulletin No. 25 – January 1973. New York (NY): The American Foundation for the Blind; 1973. p. 259–260.
- [61] Daneman M. How reading braille is both like and unlike reading print. *Mem Cognit*. 1988;16:497–504.
- [62] Davidson PW, Wiles-Kettenmann M, Haber RN, et al. Relationship between hand movements, reading competence and passage difficulty in braille reading. *Neuropsychologia*. 1980;18:629–635.
- [63] Davidson PW, Appelle S, Haber RN. Haptic scanning of braille cells by low- and high-proficiency blind readers. *Res Dev Disabil*. 1992;13:99–111.
- [64] Fertsch P. An analysis of braille reading. *Outlook Blind Teach Forum*. 1946;40:128–131.
- [65] Fertsch P. Hand dominance in reading braille. *Am J Psychol*. 1947;60:335–349.
- [66] Foulke E. Transfer of a complex perceptual skill. *Percept Mot Skills*. 1964;18:733–740.
- [67] Garcia LG. Assessment of text reading comprehension by Spanish-speaking blind persons. *Br J Vis Impair*. 2004;22: 4–12.
- [68] Heinrichs R, Moorhouse J. Touch-perception thresholds in blind diabetic subjects in relation to the reading of Braille type. *N Engl J Med*. 1969;280:72–75.
- [69] Hermelin B, O'Connor N. Functional asymmetry in the reading of Braille. *Neuropsychologia*. 1971;9:431–435.
- [70] Hislop DW, Zuber BL, Trimble JL. Text-scanning patterns of blind readers using Optacon and braille. *J Rehabil Res Dev*. 1985;22:54–65.
- [71] Holland BF. Speed and pressure factors in braille reading. *J Vis Impair Blind*. 1934;28:13–17.
- [72] Laroche L, Boulé J, Wittich W. Reading speed of contracted French braille. *J Vis Impair Blind*. 2012;106:37–42.
- [73] Loomis JM. Tactile recognition of raised characters: a parametric study. *Bull Psychon Soc*. 1985;23:18–20.
- [74] Millar S. Is there a "best hand" for braille? *Cortex*. 1984;20: 75–87.
- [75] Mommers MJC. Braille reading: factors affecting achievement of Dutch elementary school children. *J Vis Impair Blind*. 1976;70:332–340.

- [76] Mommers MJC. Braille reading: effects of different hand and finger usage. *J Vis Impair Blind*. 1980;74:338–343.
- [77] Mousty P, Bertelson P. A study of braille reading: 1. Reading speed as a function of hand usage and context. *Q J Exp Psychol A*. 1985;37:217–233.
- [78] Nakada M, Dellon L. Relationship between sensibility and ability to read braille in diabetics. *Microsurgery*. 1989;10:138–141.
- [79] Olson M, Harlow SD, Williams J. Rapid reading in braille and large print: an examination of McBride's procedures. *J Vis Impair Blind*. 1975;69:392–395.
- [80] Oshima K, Arai T, Ichihara S, et al. Tactile sensitivity and braille reading in people with early blindness and late blindness. *J Vis Impair Blind*. 2014;108:122–131.
- [81] Papadimitriou V, Argyropoulos V. The effect of hand movements on braille reading accuracy. *Int J Educ Res*. 2017;85:43–50.
- [82] Sampaio E, Philip J. Influences of age at onset of blindness on braille reading performances with left and right hands. *Percept Mot Skills*. 1995;81:131–141.
- [83] Veispak A, Boets B, Männamaa M, et al. Probing the perceptual and cognitive underpinnings of braille reading. An Estonian population study. *Res Dev Disabil*. 2012;33:1366–1379.
- [84] Wilkinson JM, Carr TH. Strategic hand use preferences and hemispheric specialization in tactual reading: impact of the demands of perceptual encoding. *Brain Lang*. 1987;32:97–123.
- [85] Wormsley DP. Reading rates of young braille-reading children. *J Vis Impair Blind*. 1996;90:278–282.
- [86] Wright T, Wormsley DP, Kamei-Hannan C. Hand movements and braille reading efficiency: data from the Alphabetic Braille and Contracted Braille Study. *J Vis Impair Blind*. 2009;103:649–661.
- [87] Braun V, Clarke V. Thematic analysis. In: Cooper H, Camic PM, Long DL, et al., editors. *APA handbook of research methods in psychology*. Volume 2. Research designs: quantitative, qualitative, neuropsychological, and biological. *APA handbooks in psychology*[®]. Washington (DC): American Psychological Association; 2012. p. 57–71.
- [88] Bertelson P. Language by touch: the case of braille reading. In: de Gelder B, Morais J, editors. *Speech and reading: a comparative approach*. Erlbaum (UK): Taylor & Francis; 1995. p. 91–108.
- [89] Golub DB. A model of successful work experience for employees who are visually impaired: the results of a study. *J Vis Impair Blind*. 2006;100:715–725.
- [90] Lorimer P. Hand techniques in reading braille; synthesis of spatial and verbal elements of reading. *Br J Vis Impair*. 2002;20:76–79.
- [91] Papagno C, Minniti G, Mattavelli GC, et al. Tactile short-term memory in sensory-deprived individuals. *Exp Brain Res*. 2017;235:471–480.
- [92] Daneman M, Carpenter PA. Individual differences in working memory and reading. *J Verbal Learning Verbal Behav*. 1980;19:450–466.

Appendix. Table of publications summarizing each study's sample characteristics, task and assessment characteristics, factors considered, and most relevant findings

Appendix.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading/ outcomes/ instruments	Modality and nature of reading task	Relevant findings
Bernbaum et al. [27]	Archives of Neurology/1989	USA/English	Design: Prospective trial; Aim: to evaluate braille reading to understand neurologic and tactile limitations in diabetic patients	$n = 35$ Diabetes Type I ($n = 22$, $M = 33$ +/- 2) - Male: $n = 9$ - Female: $n = 13$ Diabetes Type II ($n = 13$, $M = 56$ +/- 1) - Male: $n = 4$ - Female: $n = 9$	Perceptual: Tactile acuity (static two-point discrimination threshold + nerve conduction study)	Gross determination of "reading capable," "reading incapable," or "reading Jumbo braille only"	N.R.	Two-point discrimination associated with braille reading ability, but not nerve conduction study results, among patients with known diabetic neuropathies (no statistical analyses reported)
Bertelson et al. [57]	The Quarterly Journal of Experimental Psychology/1985	USA/English	Design: Cross-sectional systematic analysis; Aim: Examine hand movements used when reading	$n = 24$ Age range 18-64 - 5 female - 19 male	Motor: Hands utilized for reading and reading patterns (video examination)	Speed (reading time)	Aloud; Prose, statistical approximations, and scrambled words (with one hand, and with two hands simultaneously) - uncontracted braille	Reading patterns (one hand vs two hands) are strongly correlated with speed of reading (r with two hands separately vs together = -0.72, $p = 0.001$)
Bola et al. [11]	PLOS ONE/2016	Poland/Polish	Design: Prospective trial; Aim: Evaluate success of braille reading course for sighted adults	$n = 29$ Age range 22-49, Mdn = 27, Male: $n = 3$ Female: $n = 26$	Perceptual: Tactile acuity (GOT)	Speed (wpm)	Aloud; Character/word recognition - uncontracted braille	No correlation between GOT tactile acuity threshold and reading speed: $r(26) = -0.25$, $p = 0.206$. No correlation between age of participant and reading speed: $r(27)$ $= 0.11$, $p > 0.25$
Bradshaw et al. [58]	Neuropsychologia/ 1982	USA/English	Design: Cross-sectional study; Aims: Test left- hand superiority of blind subjects in braille reading; Assess phonological and semantic processing mechanisms	$n = 12$ Age range 28-57 Male: $n = 6$ Female: $n = 6$	Motor: Hands utilized for reading (in front of and across the body)	Speed (reading time)	Silent; Scanning (lists of boy/girl names, words/ non-words, vowels/ consonants) - uncontracted braille	No effect of hand used or hand position (cross body or not): $F(1, 11)$ $= 1.2$, $p > 0.05$.
Chen et al. [59]	Research in Developmental Disabilities/2019	China/Chinese (Common Chinese Braille)	Design: Cross-sectional study; Aim: Examine impact of hand patterns and reading mode on reading speed and comprehension	$n = 73$ Age range 11.42-22.08 ($M = 14.89$, $SD = 2.17$) Male: 49 Female: 24 48 congenital; 25 adventitious	Motor: Hands utilized for reading and reading patterns (video examination)	Speed (wpm); Comprehension (% of correct questions)	Silent and Aloud; Studying	Speed: Significant main effect for reading mode, with silent reading being faster ($F(1, 65) = 15.656$, $p < 0.001$, $\eta^2 = 0.194$); "Marginally significant" main effect for hand patterns ($F(3, 65) = 2.602$, $p = 0.059$, $\eta^2 = 0.107$). Comprehension: Significant main effect for reading mode, with silent reading leading to better comprehension ($F(1, 65) = 4.303$, $p < 0.05$, $\eta^2 = 0.062$). No main effect of reading pattern ($p > 0.05$). Adventitious vs congenital blindness not related to reading speed ($p > 0.10$) or reading comprehension ($p > 0.10$)
Clegg [60]	AFB Research Bulletin/1973	USA/English	Design: Cross-sectional study; Aim: Evaluate whether the Tactile Discrimination Test predicts ability to discriminate among braille characters	$n = 52$, all "legally blind"	Perceptual: Tactile acuity (Tactile Discrimination Test)	Accuracy (ability to recognize letters)	Modality N.R.; Discrimination of braille letters (ranked and judged by two independent certified braille instructors)	Speed: Time to complete TDT associated with braille proficiency ranking ($r = 0.62$, $p = 0.01$); Accuracy: Correct response to TDT associated with braille proficiency ranking ($r = 0.55$, $p = 0.01$)
Daneman [61]	Memory & Cognition/1988	Canada/English	Design: Cross-sectional study; Aim: to evaluate relationship between braille, listening comprehension, and working memory	$n = 31$ Age range: 23-59 ($M = 37$)	Cognitive: Listening comprehension; Braille span; Listening span	Accuracy (# of questions correct or errors detected); Speed (wpm)	Modality N.R.; Prose (reading for comprehension, and to identify out-of-context words) - contracted braille	Reading comprehension significantly associated with listening comprehension ($r = 0.49$, $p < 0.01$), braille span ($r = 0.64$, $p < 0.001$), and listening span ($r = 0.66$, $p < 0.001$), but not reading rate

(continued)

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Davidson et al. [62]	Neurophysiologia/ 1980	USA/English	Design: Cross-sectional study; Aim: examine whether haptic scanning variables impact braille proficiency	$n = 18$ Age $M = 16.38$, range 13–21 IQ $M = 92.2$, SD 14.58	Motor: Reading patterns and finger(s) used to read (video examination)	Accuracy (# of oral reading errors made); Comprehension (# of correct answers)	Aloud; Prose (reading for recall and comprehension) – contracted braille	$(r = 0.32, 0.18, 0.16$ respectively, $p > 0.05)$ Adventitious vs congenital blindness correlated with speed ($r = -0.55$, $p < 0.01$) but not comprehension ($r = 0.06$). Age correlated with speed ($r = 0.38$, $p < 0.05$) but not comprehension ($r = 0.09$) "There was ... no relationship between the use of any particular style and either the S's predetermined reading ability or the frequency of oral reading errors or retention errors." (No specific data or statistical analyses presented) High proficiency readers used two handed methods on 75% of the cells read; Low-proficiency readers used two-handed methods only on 41% of cells read ($\chi^2(1) =$ 22.35, $p < 0.01$);
Davidson et al. [63]	Research in Developmental Disabilities/1992	USA/English	Design: Cross-sectional study; Aim: Describe scanning movements (pauses, regressions, forward movements) of braille readers	$n = 16$, Age $M = 16.5$ (range 13–21), IQ $M = 92.2$ ($SD = 14.6$), divided into low- and high-proficiency groups based on Wide Range Achievement Test (WRAT)	Motor: Reading patterns – forward scanning, pausing, regressing (video examination)	Speed: Measured in cells per second	Aloud; Prose passages (source and content unspecified) – contracted braille	"Using both hands together to make regressive movements is a distinguishing characteristic of poor readers." (No specific data or statistical analyses presented)
Fertsch [64]	Outlook for the Blind aka Journal of Visual Impairment & Blindness/1946	USA/English	Design: Cross-sectional study; Aim: Examine whether hand/finger use and movements during reading predict proficiency	N.R.	Motor: Reading patterns – forward regressing (video examination)	Speed: measure N.R.	Aloud and Silent; Prose passages – contracted vs uncontracted not reported	Handedness did not correlate with hand reading preferences or dominance; Readers whose hands were equal or who dependant mainly on their right hand read faster than readers dependant upon their left hand ($p < 0.05$); Individuals with significant hand dominance (i.e., % of cells read with the right or left hand being much greater than the opposing hand) read more slowly when forced to read with only one hand ($p < 0.05$)
Fertsch [65]	American Journal of Psychology/1947	USA/English	Design: Cross-sectional study; Aim: determine which hand plays a greater role in reading and assess right/left hand superiority	$n = 63$ – 33 male – 30 female	Motor: Handedness (preference for throwing a ball); Hands utilized for reading (video examination)	Speed (reading time)	Silent and Aloud; Prose (reading for comprehension) – contracted vs uncontracted not reported	No relationship between hand used and reading speed ($F(1) = 3.79$, $p > 0.05$) or accuracy ($F(1) = 2.97$, $p > 0.05$); As one moves away from the index finger for reading, degradations in speed ($F(3) =$ 103.92, $p < 0.01$) and accuracy ($F(3) =$ 112.43, $p < 0.01$) are observed
Foulke [66]	Perceptual and Motor Skills/1964	USA/English	Design: Prospective study; Aim: to evaluate transfer of braille reading ability from the index finger to others	$n = 12$ Age range 29–62 ($M = 47.08$, $SD = 9.53$) – 3 male – 9 female	Motor: Finger used to read	Speed of reading (wpm), Speed of letter identification (reading time), Accuracy of letter identification (# of errors)	Silent (for speed) + Aloud (for experimental condition); Prose (reading for comprehension, to determine reading speed); Random letter identification with various fingers (experimental task) – contracted vs uncontracted	No significant difference in comprehension across reading pattern groups ($F = 0.64$);
Garcia [67]	British Journal of Visual Impairment/2004	Spain/Spanish	Design: Prospective study; Aim: examine whether cloze or formal passage	$n = 13$ Age: $M = 44$ 11 male, 2 female	Motor: Reading patterns (one handed vs	Speed (wpm), Comprehension (# correct answers)	Modality N.R.; Prose (reading for	No significant difference in comprehension across reading pattern groups ($F = 0.64$);

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Appendix. Continued.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Heinrichs [68]	New England Journal of Medicine/1969	Canada/English	Design: Cross-sectional study; Aim: explore the impact of diabetic neuropathy on touch perception	Non-diabetic: $N = 10$ (6 male, 4 female, age $M = 30$, $SD = 9$); Diabetic: $N = 10$ (6 male, 4 female, $M = 31$, $SD = 9$)	Perceptual: Sensitivity to vibration with light touch ("touch perception") and heavy contact ("proprioception") Perceptual: Tactile acuity (Semmes-Weinstein nylon filament test) Perceptual: Tactile acuity (Two-Point discrimination (static)) Motor: Reading hand and finger used	Capacity (measured subjectively as "learned readily," "moderate difficulty," "great difficulty," "couldn't learn," "didn't try")	N.R.	Statistically significant difference between one-handed readers and two-handed disjoint readers ($t = 3.15$, $p < 0.05$) Years of braille reading experience/age when braille learned was correlated with reading speed ($C = 0.518$, $p = 0.037$) but not reading comprehension ($C = 0.250$, $p = 0.549$) "Subjects with marked elevation of touch-perception thresholds at their fingertips were scarcely able to feel the type at all" (Conclusory statement only; Raw data but no statistical analyses presented) NOTE: Nakada [78] subsequently describes this as a statistically significant difference ($p < 0.02$).
Hermelin et al. [69]	Neuropsychologia/ 1971	England/English	Study #1: Design: Cross- sectional study; Aim: examine transfers of braille reading ability to non-preferred fingers/hand	$N = 16$, age range 8–10	Motor: Reading hand and finger used	Speed (time taken); Accuracy (error count)	Modality N.R. but assumed to be aloud; Reading individual words and sentences – contracted braille	Speed: Index fingers were superior to other fingers ($p = 0.001$); Left hands were significantly faster than right ($F = 12.99$, $p < 0.001$); Left index was significantly faster than right index ($t = 2.18$, $p < 0.05$); Left middle was significantly faster than right middle ($t = 2.90$, $p < 0.02$) Accuracy: No significant difference between index fingers; Significant difference between left and right middle fingers ($t = 2.45$, $p < 0.05$) Speed: No significant difference (data and analyses N.R.) Accuracy: Significantly fewer errors were made with the left than the right hand (partial $F = 6.98$, $p = 0.02$) Reading with two hands was marginally faster than with one (no statistical analysis reported)
Hislop et al. [70]	Journal of Rehabilitation Research and Development/1985	USA/English	Study #2: Design: Cross- sectional study; Aim: examine speed and accuracy of reading with non- preferred fingers Design: Cross-sectional; Aim: to explore hand usage/reading patterns	$N = 15$, age range 25–65, 7 male, 8 female $N = 20$ (early 20s – 1 subject in her 60s, and a number of participants over 30)	Motor: Reading hand and finger used Motor: Reading patterns (one vs two handed) (horizontal/vertical position measured with a position sensing system and finger- mounted LEDs)	Speed (number of characters read in allotted time); Accuracy (error count) Speed (wpm)	Modality N.R. but assumed to be aloud; Reading randomized permutations of the alphabet – uncontracted braille Silent; Prose (reading for comprehension) – contracted braille	Speed: Index fingers were superior to other fingers ($p = 0.001$); Left hands were significantly faster than right ($F = 12.99$, $p < 0.001$); Left index was significantly faster than right index ($t = 2.18$, $p < 0.05$); Left middle was significantly faster than right middle ($t = 2.90$, $p < 0.02$) Accuracy: No significant difference between index fingers; Significant difference between left and right middle fingers ($t = 2.45$, $p < 0.05$) Speed: No significant difference (data and analyses N.R.) Accuracy: Significantly fewer errors were made with the left than the right hand (partial $F = 6.98$, $p = 0.02$) Reading with two hands was marginally faster than with one (no statistical analysis reported)
Holland [71]	Journal of Visual Impairment & Blindness/1934	USA/English	Design: Prospective study; Aim: explore relation of pressure to speed	$N = 17$, pupils in grades 4–10 (estimated 9–15 years old)	Motor: Pressure/contact force of finger on reading material at start/mid/end of line)	Speed (time to read)	Modality N.R.; Prose (7-line passages from the Stanford Achievement Reading Test) – uncontracted vs contracted braille not reported	Positive correlation observed between pressure and reading speed ($r = 0.27$), but non-significant (and questionable given that overall, better/faster readers tended to use less and more consistent force)
Laroché et al. [72]	Journal of Visual Impairment & Blindness/2012	Canada/French	Design: Cross-sectional study; Aim: assess impact of reading modality, age of learning braille, and	$n = 30$ Age range: 18–67 ($M = 40.9$, $SD = 3.1$) 15 male, 15 female	Motor: Reading hand used/hand patterns (one vs two handed)	Speed (wpm)	Silent and Aloud; Prose (newspaper article, novel passage) – contracted braille	Two-handed readers were faster, especially if they used the "scissors" pattern ($F(1, 10) = 12.91$, $p = 0.005$) Age of first learning braille correlated with reading speed ($F(1, 28) = 8.07$,

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Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Legge et al. [9]	Perception & Psychophysics/2008	USA/English	Study #1: Design: Prospective study; Aim: explore correlation between a novel measure of tactile acuity and age in braille readers Study #2: Prospective study; Aim: explore correlation between a novel measure of tactile acuity and age in braille readers	$n = 49$ Age range: 18–74, $M = 44.3$, $SD = 15.2$	Motor: Hand used; Perceptual: Tactile acuity (Legge Dot Chart)	Speed (wpm)	Aloud: Sentence reading (MNRREAD) – contracted braille	$p = 0.008$, $\eta^2 = 0.40$). Those who learned braille before age 10 made significantly more errors when reading aloud ($t(20) = 2.08$, $p = 0.05$, $\eta^2 = 0.18$), but comprehension was unimpacted (no statistics reported). Neither “hand used” nor Legge Dot Chart acuity was associated with reading speed ($p > 0.06$)
Loomis [73]	Bulletin of the Psychonomic Society/1985	USA/English	Design: Prospective study; Aim: evaluate legibility of braille mediated by dot height, mode of touch (static or moving), character size, and contact force	$n = 6$ Age: 21–27 All female	Motor: Contact force	Accuracy (% correct)	Aloud; Discrimination of individual braille letters – uncontracted braille	No significant correlation between braille reading speed and tactile acuity ($p > 0.70$) Contact force/pressure (16–28 g or 75–125 g) was not associated with reading accuracy (48.5% vs 48.9% accuracy – no statistical analysis presented)
Millar [74]	Cortex/1984	USA/English	Study #1: Design: Cross- sectional; Aim: examine impact of laterality on braille reading	$n = 20$ Age: $M = 9.54$ (range 6.0 – 11.83)	Motor: Hand used	Speed: Reading time (response latency); Accuracy (% correct)	Aloud; Same/different matching; Discrimination of individual braille letters – uncontracted braille	No significant effect of Hand on accuracy/errors, but task type (matching vs letter discrimination) showed an interaction with hand used ($F(1, 12) = 32.32$, $p < 0.001$). For speed, better readers showed a right-hand advantage for letter naming ($p < 0.025$) and discrimination tasks ($F(1, 12) =$ 5.55 , $p < 0.05$); poor readers showed a left-hand superiority for discrimination tasks ($p < 0.025$). No significant effect of Hand on speed ($F(1, 12) = 3.74$, $p > 0.05$ but < 0.10), but pre- planned t -tests suggested that one- handed reading was inferior to reading with either hand alone ($p < 0.025$)
Mommers (1976) [75]	Journal of Visual Impairment & Blindness/1976	Holland/Dutch	Design: Cross-sectional study; Aim: validating correlates to standardized braille reading tests in Holland	$N = 120$, age 6–14	Perceptual: Tactile acuity (Roughness Discrimination Test (RDT); Tactile Kinesthetic Form Discrimination Test (TKFDT); Haptic Size Discrimination Test (HSDT); Haptic Figure Orientation Test (HFOT); Haptic Object Discrimination Test (HODT)	Speed (measure N.R.)	Aloud: Reading lists of words, sentences, and short stories – uncontracted braille	No significance testing reported. For speed, correlations (for reading words/sentences) reported as follows: RDT = 0.24/0.20 TKFDT = 0.43/0.42 HSDT = 0.30/0.26 HFOT = 0.49/0.47 HODT = 0.51/0.49

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Appendix. Continued.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Mommers (1980) [76]	Journal of Visual Impairment & Blindness/1980	Holland/Dutch	Design: Cross-sectional; Aim: evaluate division of labour between both hands (replication of [69])	$N = 25$; age range 7.5–12	Motor: Hand and finger used	Speed (# words read, correctly or incorrectly, in 2 min + # of numerals read, correctly or incorrectly, in 1 min); Accuracy (# of errors in first 50 words or numerals);	Aloud; Reading lists of words and numerals – uncontracted braille	Two hands together were “clearly faster than even the fastest index finger” alone for words and numerals: $t(24) = 7.02$ for words, $t(24) = 4.35$ for numerals, $p = 0.005$. No statistically significant difference for accuracy. No significant difference between right index finger and left index finger or right middle finger and left middle finger alone (for speed or accuracy). However, the data presented supports a “trend for left-handed reading of words to be faster and more accurate.”
Mousty and Bertelson [77]	The Quarterly Journal of Experimental Psychology/1985	Belgium/French	Design: Cross-sectional study; Aim: consider how reading speed is affected by hand usage and reading context	$n = 24$ 5 male, 19 male Age range: 18–64	Motor: Hand (or hands) used	Speed (wpm)	Aloud; Prose (novel passages); Approximations to French; Scrambled words – uncontracted braille	Use of two hands is faster than one (but not statistically significant: $F(2,$ $21) = 1.47, p > 0.10$); otherwise, there was no effect of hand(s) Mean reading speed is higher for congenitally blind when reading with left hand ($t(22) = 1.79,$ $p < 0.05$) and both hands together ($t(22) = 1.19, p < 0.1$).
Nakada and Deillon [78]	Microsurgery/1989	Japan/Japanese	Design: Cross-sectional; Aim: evaluation tactile acuity and reading performance after 2 years of training	$n = 25$ Age: range 18–58, $M = 42.6, SD = 10.2$	Perceptual: Tactile acuity (Semmes-Weinstein nylon filament test, in both static/passive and moving/active modes); Static two-point discrimination; Two- point discrimination (moving)	Capacity (measured subjectively as “good” (sentence reading), “fair” (word reading), or “unable”)	N.R.	No difference between good/fair readers across all tactile acuity tests; Significant difference ($p < 0.001$) in acuity levels between “unable” and “good/fair” groups on both moving and static two-point discrimination. Age/age braille learned significantly related to capacity for reading ($F(2,$ $22) = 3.956, p = 0.341$) (NOTE: Japanese braille dot spacing is more compact than US/European braille and these results may not carry over to standard US/European braille formats.)
Nolan and Morris [8]	The International Journal for the Education of the Blind/1965	USA/English	Design: Prospective study; Aim: determine whether results from Roughness Discrimination Test predict reading readiness	$n = 256, 133$ male, 123 female, age range 6–12.3	Cognitive: IQ; Perceptual: Tactile acuity (Roughness Discrimination Test)	Speed (reading time), Accuracy (# of errors)	N.R.	Correlations reported between RDT scores and reading speed (-0.42) and error performance (-0.42) ($p < 0.05$) For students in grade two, multiple correlation including RDT performance and IQ yielded a stronger relationship to speed ($r = 0.48$) and accuracy ($r = 0.51$). The use of more than one finger in the braille reading process was positively correlated with an increase in reading rate ($p < 0.05$). No significant differences in speed found based on age. Age was significantly positively correlated with comprehension. (No statistics reported.)
Olson et al. [79]	Journal of Visual Impairment & Blindness/1975	USA/English	Design: Prospective study; Aim: explore impact of structured rapid reading training on speed and comprehension	Missouri group: $n = 15, 11$ female, 4 male, age 19–62 ($M = 38.6$) North Dakota group: $n = 12, 8$ female, 4 male, age 10–65 ($M = 34.2$)	Motor: Hand movements (number of fingers used)	Speed (reading rate)	Aloud; Reading prose selections from the Diagnostic Reading Scales test – contracted vs uncontracted braille not reported	No relationship found between tactile acuity and braille reading speed (when controlling for number of
Oshima et al. [80]	Journal of Visual Impairment & Blindness/2014	Japan/Japanese	Design: Cross-sectional study; Aim: examine relationship between	$n = 19$ Early blind ($n = 9$): – 5 male, 4 female	Perceptual: Tactile acuity (Legge “Dot” Chart,	Speed (reaction time), Accuracy (% correct answers),	Aloud; Word reading (2- cell words); Prose reading; Scrambled	(when controlling for number of

(continued)

Appendix. Continued.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Papadimitriou and Argyropoulos [81]	International Journal of Educational Research/2017	Greece/Greek	Design: Cross-sectional study; Aim: explore relationship between hand movements and accuracy	– Age: Range 23–59, $M = 41.3$ ($SD = 10.5$) Late blind ($n = 10$): – 3 male, 7 female – Age: Range 20–65, $M = 45.1$ ($SD = 16.4$)	adapted for Japanese braille spacing)	Motor: Hand movements used	word reading: Numerical passage reading – uncontracted braille	years reading braille ($r = -0.46$, $p < 0.05$), age of onset of blindness ($r = -0.08$, ns), or both ($r = 0.04$, ns). Age of learning braille significantly influenced speed ($F(1, 17) = 7.648$, $p < 0.05$; $\eta^2 = 0.24$) but not accuracy. (NOTE: Japanese braille dot spacing is more compact than US/European braille and these results may not carry over to standard US/European braille formats.)
Sampaio and Philip [82]	Perceptual and Motor Skills/1995	France/French	Design: Cross-sectional study; Aims: To explore whether prior visual experience influenced laterality advantages; and to verify impact of hand preference in one-handed reading	$n = 32$, 18 female, 14 male, age $M = 14.2$ ($SD = 3.3$), range 8–21	Motor: Use of non- preferred reading hand	Accuracy: Number of errors in reading	Aloud; Reading prose – uncontracted braille	Braille reading patterns affected the number of errors (chi-sq (12) = 95.7, $p < 0.001$)
Stevens et al. [10]	Journal of Experimental Psychology: Applied/1996	USA/English	Design: Cross-sectional study; Aim: to explore tactile acuity, the effects of aging, and the impact on reading performance	$n = 38$ All right-handed participants Congenitally blind: – Age 19–62, $M = 33.9$ – 12 female, 9 male Early childhood blindness: – Age 20–50 ($M = 34.4$) – 10 female, 7 male	Perceptual: Tactile acuity (Gap Detection, Two- point Discrimination (static), Two-point Orientation)	Speed (reading time)	Aloud; Scanning (lists of 5- letter words, matched for braille legibility) – uncontracted braille	Among those blind at birth, those who preferred to read with the right hand performed better with this hand than with the left (when forced to read with one hand); those who preferred to read with the left hand performed better with this hand than with the right. This was not observed among those who lost their vision in early childhood. Congenital group: left preference, $F(1,10) = 6.97$, $p < 0.03$; right preference: $F(1,8) = 7.09$, $p < 0.03$. Early childhood group: left preference: $F(1,4) = 3.16$, ns; right preference: $F(1,7) = 3.51$, ns A difference in speed was observed between the congenital and early childhood groups: $F(1, 34) =$ 6.89 , $p < 0.01$
Stevens et al. [10]	Journal of Experimental Psychology: Applied/1996	USA/English	Design: Cross-sectional study; Aim: to explore tactile acuity, the effects of aging, and the impact on reading performance	Study #1: $n = 33$ – Age 18–81 ($M = 48.6$, $SD = 16.2$)	Perceptual: Tactile acuity (Gap Detection, Two- point Discrimination (static), Two-point Orientation)	Speed (wpm)	Silent; Sentences and words (Tinker-Carver Basic Reading Rate Scale) – uncontracted vs contracted braille not specific	Reading rate significantly correlated with gap detection ($r = -0.54$, $p = 0.002$) and two-point orientation ($r = -0.36$, $p < 0.05$); Two-point discrimination threshold was not (r = -0.16 , $p = 0.41$)
Stevens et al. [10]	Journal of Experimental Psychology: Applied/1996	USA/English	Design: Cross-sectional study; Aim: to explore tactile acuity, the effects of aging, and the impact on reading performance	Study #2: $n = 36$ Younger Group ($n = 15$) – Age 19–34 Older Group ($n = 21$) – Age 60–82	Perceptual: Tactile acuity (Two-Point Gap Discrimination, Line Orientation, Length Discrimination)	Speed (wpm)	Silent; Sentences and words (Tinker-Carver Basic Reading Rate Scale) – uncontracted vs contracted braille not specific	Two-point Gap Discrimination significantly inversely related to reading rate among older participants ($r = -0.48$, $p < 0.04$); Line Orientation and Line Discrimination were not (statistics not reported).
Weispak et al. [83]	Research in Developmental Disabilities/2012	Estonia/Estonian	Design: Cross-sectional study; Aim: to investigate associations between auditory, speech, phonological and tactile spatial	$n = 12$ Age Range 9–19.5, $M = 14.25$, $SD = 3.25$	Perceptual: Tactile acuity (Grating Orientation Test, GOT); Cognitive: Phonological awareness (phoneme deletion and spoonerism task);	Speed (measure not specified)	Aloud; Word and pseudoword reading – uncontracted braille	– Word-reading speed significantly correlated with phonological awareness (speed) ($r = 0.74$, $p < 0.05$), rapid automatic naming ($r = 0.81$, $p < 0.01$), and tactile acuity (GOT) ($r = 0.70$, $p < 0.05$) – Pseudoword-reading speed

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Appendix. Continued.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Veisapak et al. [12]	Research in Developmental Disabilities/2013	Holland/Dutch	Design: Cross-sectional study; Aim: to investigate associations between auditory, speech, phonological and tactile spatial processing, and reading performance	$n = 28$ Age: $M = 15.5$ ($SD = 3.5$), 7 female, 7 male	Perceptual: Tactile acuity (Grating Orientation Test); Cognitive: Verbal Intelligence, Phonological Processing (phoneme deletion), Verbal Short- term Memory, Speech Perception	Speed (reading time); Accuracy (number of errors)	Aloud; Word, pseudoword, and story reading	significantly correlated with phonological awareness (speed) ($r = 0.80$, $p < 0.01$) and rapid automatic naming ($r = 0.70$, $p < 0.05$) – Word-reading accuracy not significantly correlated with phonological awareness (speed or accuracy: $r = 0.33$ and 0.45), verbal short term memory ($r = 0.17$), rapid automatic naming ($r = 0.12$), speech-in-noise ($r = 0.01$), or tactile acuity ($r = 0.50$) – Pseudoword-reading accuracy correlated with phonological awareness (accuracy) ($r = 0.66$, $p < 0.05$), verbal short-term memory ($r = 0.64$, $p < 0.05$), rapid automatic naming ($r = 0.64$, $p < 0.05$), speech- in-noise ($r = 0.75$, $p < 0.05$), and tactile acuity (GOT) ($r = 0.66$, $p < 0.1$) – Phonological awareness accuracy correlated with word reading accuracy ($r = 0.47$, $p < 0.05$), pseudoword reading accuracy ($r = 0.55$, $p < 0.01$), story reading accuracy ($r = 0.53$, $p < 0.01$), and marginally with story reading speed ($r = 0.34$, $p < 0.10$) – Phonological processing speed was not correlated with reading performance on any measure (r < 0.27) – Verbal short-term memory significantly correlated with word reading accuracy ($r = 0.41$, $p < 0.05$), pseudoword reading accuracy ($r = 0.52$, $p < 0.01$), story reading accuracy ($r = 0.40$, $p < 0.05$) – Tactile acuity (GOT) was significantly correlated with word reading speed ($r = 0.45$, $p < 0.05$) and marginally with story reading speed ($r = 0.38$, $p < 0.10$)
Wilkinson and Carr [84]	Brain and Language/1987	USA/English	Design: Cross-sectional; Aim: examine impact of using non-preferred hand for reading	$n = 63$ (34 male, 29 female) – Congenitally blind or lost vision $< = 2$ years old – 41 were students in residential schools for the blind (age 11–18); – 22 were adult volunteers (age 19–70)	Motor: Handedness (Edinburgh) and hand preference; Hand and fingers used and hemispheric position relative to body; Cognitive: Short-term memory test (oral repetition of words); Comprehension test with concurrent memory load	Speed (reading time); Accuracy (number of errors)	Aloud; Word reading; Letter identification; Same/different matching; Passage reading (24 2–3 sentence paragraphs)	– Letter identification: hand use/hand preference impacted speed ($F(1,55)$ $= 14.56$, $p < 0.001$) and accuracy ($F(1, 55) = 13.53$, $p < 0.001$) – but a four-factor interaction between hand use, hand preference, sex, and order of hand use was also found, $F(1, 55) = 7.31$, $p < 0.05$. – Same/different matching: For “easy” lists, hand use and hand preference impacted speed ($F(1, 55) = 5.66$, $p < 0.05$), but not accuracy. For “hard” lists, hand use/hand preference were significant for both

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Appendix. Continued.

Study	Journal/ publication year	Country/ language	Study design and objective	Sample size/ characteristics	Measured capacities/ instruments	Measured reading outcomes/ instruments	Modality and nature of reading task	Relevant findings
Wormsley [85]	Journal of Visual Impairment & Blindness/1996	USA/English	Design: Cross-sectional study; Aim: to determine whether a hand-movement training program increased reading rates	$n = 22$ Age 6–12	Cognitive: IQ; Motor: Hand movement patterns	Speed (wpm)	Aloud; Passage reading – contracted vs uncontracted braille not specified	speed ($F(1, 55) = 9.59, p < 0.01$) and accuracy ($F(1, 55) = 6.32,$ $p < 0.05$). – Recall lists: Phonological similarity of lists increased reading speed ($F(2,$ $118) = 7.15, p < 0.01$) – Comprehension under concurrent memory load: Hand use and hand preference demonstrated a robust relationship with reading times ($F(1,$ $55) = 34.49, p < 0.001$), but no significant results for accuracy – Category 6 (both hands reading, the left for the first half of the line and the right for the second half of the line) “is associated with fastest reading rates” (raw data but no statistical analyses presented) – Reading rate was significantly impacted by hand pattern use ($F(12,$ $27) = 3.99, p < 0.01, r^2 = 0.76$) – Reading speed of two-handed readers increased significantly more quickly than for one-handed readers over time (i.e., starting with a two- handed method lead to greater gains in the long run): $B = 7.21, p < 0.05$
Wright et al. [86]	Journal of Visual Impairment & Blindness/2009	USA and Canada/English	Design: Normalized five- year longitudinal; Aim: examine impact of hand movement patterns on reading speed	$n = 38$ 15 male, 23 female Age (first year) $M = 5.33,$ range 3–7 Age (final year) $M = 8.51,$ range 7–11	Motor: Hand(s) used for reading; Movement patterns; Movement characteristics (regressions, scrubbing, etc.)	Speed (wpm)	Aloud; Passage reading; Reading included uncontracted, partially contracted, and fully contracted materials	

N.R: not reported.