UC Berkeley
UC Berkeley Electronic Theses and Dissertations

Title

The Development and Validation of a Tactile Processing Speed Measure

Permalink

https://escholarship.org/uc/item/0q13296s

Author

McKerracher, Amanda Lee

Publication Date

2014

Peer reviewed|Thesis/dissertation

The Development and Validation of a Tactile Processing Speed Measure

By

Amanda Lee McKerracher

A dissertation submitted in partial satisfaction of the

requirements of the degree of

Doctor of Philosophy

in

Education

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Frank C. Worrell, Chair
Professor Aki Murata
Professor Silvia Bunge

Spring 2014

Abstract

The Development and Validation of a Tactile Processing Speed Measure

by

Amanda Lee McKerracher

Doctor of Philosophy in Education

University of California, Berkeley

Professor Frank C. Worrell, Chair

Processing speed refers to the cognitive ability that is involved in fluently performing cognitive tasks with simple stimuli. Individual differences in processing speed can predict performance on tests of complex cognitive functions such as memory and fluid reasoning, as well as performance on academic tests in reading, writing, and mathematics. For this reason, measures of processing speed are included in most cognitive assessment batteries. However, extant measures of processing speed rely on visual stimuli, making them inaccessible to individuals with visual impairments. The current study describes the adaptation of one of the most commonly used processing speed measures, WISC-IV Coding, into a tactile task. Using a sample of 19 high school students (M_{age} = 15.74) with visual impairments who use braille as their primary literacy medium, have no additional disabilities, and are on track to receive their high school diploma by age 22, preliminary validation analyses were conducted. Split-half reliability calculations showed that scores on the instrument were reliable (α = .92). Additional instruments were administered – including the KeyMath-R braille adaptation, DIBELS braille reading fluency, and the Blind Learning Aptitude Test – to examine convergent and discriminant validity, and results provided evidence of convergent validity. Implications for practice and future directions for research are discussed.

<center>**The Validation of a Tactile Processing Speed Measure**</center>

The measurement and understanding of individual differences in the speed of cognitive processing were among the earliest empirical ventures in psychology (Jensen, 2006). Wilhelm Wundt (1832–1920), one of the forefathers of the discipline, focused a large portion of his scholarly career on a phenomenon known as *reaction time*. Reaction time refers to "the speed with which subjects make judgments" about basic stimuli (Gazzaniga, Ivry, & Mangun, 2008, p. 113). A sample modern reaction time task might require a participant to press a key when a circle appears on a computer screen. Reaction time tasks are typically scored in two ways: accuracy (i.e., number of items completed correctly) and latency (i.e., delay in responding; Sattler, 2008). Accuracy tends to be high across participants, given the simplicity of the stimuli and task demands. Latency varies across participants and tends to be normally distributed.

In modern psychology, reaction time tasks fall under a larger category known as *processing speed* tasks. Processing speed refers to "the ability to fluently and automatically perform cognitive tasks, especially when under pressure to maintain focused attention and concentration" (Flanagan, Ortiz, & Alfonso, 2007, p. 291). Most modern intelligence tests include at least one measure of processing speed because of its theoretical and empirical implication as a subcomponent of intelligence (McGrew, 1997; Taub & McGrew, 2004). However, all existing processing speed tasks involve visual stimuli (Flanagan, Ortiz, & Alfonso, 2007), making them inaccessible to individuals with visual impairments.

The purpose of the current study is to describe the development and subsequent validation of a tactile measure of processing speed. The sections that follow summarize research on the nature of processing speed and how it is measured. Next, the test development process is described, outlining the adaptation of the WISC-IV Coding subtest into a tactile measure. Drawing from research with sighted samples, the relationship between processing speed and other cognitive and academic skills is summarized, leading to the generation of hypotheses about the relationship between these skills for individuals with visual impairments. Using these hypotheses, reliability and validity analyses are summarized, providing preliminary validation evidence for the tactile processing speed measure.

The Nature of Processing Speed

For the purpose of this study, processing speed will be used to refer to a wide group of speeded cognitive processing abilities, including reaction time, decision speed, psychomotor speed, and comparison speed. In factor analyses of cognitive processing tasks that appear on various assessment tools, these skills tend to load on a single factor, henceforth referred to as processing speed (Flanagan et al., 2007). However, researchers and theorists have discriminated between simple processing speed and complex processing speed (Deluca & Kalmar, 2008). Simple processing speed (often referred to as reaction time) tasks often require an individual to respond to a stimulus as quickly as possible, but do not require complex decision making or information processing to respond correctly. For example, in a simple processing speed task, an individual may be asked to press a button as soon as possible after a stimulus is displayed on a screen or after an auditory tone is presented.

In contrast, complex processing speed tasks rely to some extent on the ability to efficiently and quickly process information before responding. Such tasks may involve learning novel, yet relatively simple, symbol-referent relationships and using this information to speedily respond to task demands. Research has supported this discrimination and researchers have

<center>1</center>

asserted that processing speed is not a unitary construct and that multiple measures should be utilized in a clinical context (Chiaravalloti, Christodoloulou, Demaree, & DeLuca, 2003). The focus of the current examination is complex processing speed.

The description of complex processing speed tasks as requiring efficient information processing prior to responding may seem similar to working memory tasks. However, Martin and Bush (2008) discriminated between the two skills by characterizing working memory as "a limited capacity memory system that provides temporary storage to manipulate information for complex cognitive tasks" (p. 30), whereas processing speed is defined as "the time required to execute a cognitive task or the amount of work that can be completed within a time frame" (p. 31). Indeed, factor analytic research has supported the notion that these are two separate constructs (e.g., McGrew, 2009; McGrew & Flanagan, 1998; Newton & McGrew, 2010; Taub & McGrew, 2004). Thus, although these two skills are interrelated in real world cognitive processing, they are not identical constructs and clinical processing speed tasks can be devised that rely only minimally on working memory capacity.

The Implications of Individual Differences in Processing Speed

Salthouse (1996) presented a theory regarding the relationship between processing speed and other, higher order cognitive skills. In essence, he described two mechanisms through which poor processing speed may affect higher order processing. The first hypothesized mechanism is titled the "limited time mechanism" (Salthouse, 1996, p. 403). The limited time mechanism suggests that poor processing speed will limit the ability to complete higher order cognitive processing for any timed task, even if the task is not ostensibly a measure of processing speed or reaction time. The second theorized mechanism is titled the "simultaneity mechanism" (Salthouse, 1996, p. 403). The simultaneity mechanism suggests that poor processing speed will affect later processing on untimed tasks because information that is not speedily processed at the beginning of a task will be lost before it can be acted upon.

Developmental evidence for the simultaneity mechanism has been presented by Fry and Hale (1996, 2000) and Luna, Garver, Urban, Lazar and Sweeny (2004). Both groups of researchers suggest that processing speed and working memory develop independently and mature at different points. The development of working memory (which matures later than processing speed) can be influenced by individual differences in processing speed, as faster processing contributes to a more efficient working memory. A more thorough discussion of the relationship between processing speed and other cognitive abilities, as well as processing speed's relationship to outcome measures such as academic achievement in reading, writing, and mathematics is included later in the introduction.

Processing Speed Interventions

Given that processing speed appears to have implications for working memory and higher level cognitive processing, the possibility of improving processing speed is attractive. Improving processing speed may have implications beyond performance on processing speed tasks, potentially demonstrating concomitant improvements in areas of cognitive functioning reliant on processing speed. Despite a recent proliferation of research on cognitive training, the idea that basic cognitive abilities can be trained and improved remains controversial. Proponents cite recent studies showing significant improvements on cognitive tasks following training programs as evidence that cognitive abilities can be improved (e.g., Nouchi et al., 2012). Critics argue that, by and large, the results of these training programs have not been shown to transfer beyond

improvements on cognitive tasks to real world situations, and that the sustainability of these gains after training is questionable (e.g., Owen et al., 2010).

Some of the earliest processing speed training research took place within a geriatric population. Edwards et al. (2002) examined the effectiveness of speed of processing training on processing speed performance. Using a pre/post design, a sample of 49 older adults (M_{age} = 73.71) underwent six weeks of processing speed training. A matched group of 48 participants acted as a control group. The training involved computerized tasks of simple speed of processing, divided attention, and selective attention. These tasks were similar to, but not identical to the measures of processing speed used during pre- and post-testing. Results indicated that, compared to the control group, participants in the experimental group showed increased performance on the measure of processing speed, but not on measures of other areas of cognitive processing. This finding suggests that the training was uniquely effective in improving only processing speed abilities.

Subsequent research with younger samples has shown that processing speed may be malleable in children as well. Mackey, Hill, Stone, and Bunge (2011) randomly assigned 17 children ages 7 to 10 to a reasoning training program and 11 children to a processing speed training program. A pre/post design was used, with measures of fluid reasoning and processing speed, among other cognitive skills, administered before and after the training program. Training involved the use of board and video games, classified according to their emphasis on reasoning or speed. Results showed a double dissociation between training groups. Children in the reasoning training group scored significantly better on the post-test administration of fluid reasoning tasks, but not processing speed tasks. In contrast, children in the processing speed training group scored significantly better on the post-test administration of processing speed tasks, but not fluid reasoning tasks. These results suggest that processing speed is modifiable through training even among children. Similar work supporting the use of video games to train and improve processing speed among children has been reported by Dye, Green, and Bavelier (2009) and Diamond and Lee (2011).

The research summarized in this section suggests that processing speed may be a trainable skill. Given the importance of processing speed in relation to other cognitive abilities in timed tasks, the potential to remediate poor processing speed is encouraging. However, extant research does not support the notion that improvements in processing speed after training generalize to other cognitive abilities or to academic achievement. Future research in this area should seek to explore whether post-training improvements in processing speed generalize to other cognitive and academic skills of interest. At present, a conservative interpretation of the available research suggests that training can improve performance on measures of processing speed.

The Need for a Tactile Processing Speed Measure

The previous section has established that processing speed is a measurable cognitive ability. Further, processing speed appears to be a trainable skill, allowing for potential interventions for children who display slow processing speed. However, all measures of processing speed on the most commonly used assessments of cognitive abilities rely upon visual stimuli. Flanagan et al. (2007) included a list of measures of processing speed from the Cognitive Assessment System (CAS), Wechsler Intelligence Scale for Children (WISC-IV), Woodcock-Johnson Test of Cognitive Abilities (WJ-III), Leiter-R, and the Differential Abilities Scales (DAS-II), and reported that all rely on visual stimuli. However, for students with visual

impairments, tasks with visual stimuli are inaccessible. Thus, given that all processing speed instruments rely on visual stimuli, there are currently no instruments available to measure processing speed among students with visual impairments. Further, a search of the research literature suggests that there is no evidence that any such test has been previously developed.

Because processing speed appears to have a relationship with other cognitive abilities in timed-test environment, and because poor processing speed appears to be remediable, the inability to measure the processing speed of visually impaired students becomes an issue of inequity. Indeed, Section 614 of the Individuals with Disabilities Education Act (IDEA) states that "A State educational agency, other State agency, or local educational agency shall conduct a full and individual initial evaluation, in accordance with this paragraph and subsection (b), before the initial provision of special education and related services to a child with a disability under this part." However, without appropriate assessment tools in all areas, a full and individual evaluation of students with visual impairments is not possible.

Measure Development

This section outlines the adaptation of one of the most common processing speed measures – WISC-IV Coding – into a tactile format. The WISC-IV is one of the most commonly used measures of intellectual functioning of children in the United States (Wechsler, 2003). The Coding subtest is one of two measures of processing speed on the WISC-IV. Coding was selected based on the reliability and validity of the scores (Wechsler, 2003; $\alpha = .85$) as well as the ease of adapting the task into a tactile format. The goal was to adapt the task in such a way that stimuli, but not task demands, were changed.

Symbol selection. To select appropriate tactile stimuli for the adaptation, research on the tactile discernibility of symbols was consulted. Tactile symbols are often used in maps developed for individuals with visual impairments, so the majority of research in this area focuses on tactile cartography. Lambert and Lederman (1989) conducted empirical studies of the legibility of tactile map symbols, based on earlier work in Lambert's (1984) dissertation. The researchers combined previously studied and newly developed tactile symbols. In Study 1, Lambert and Lederman examined the optimal size of tactile symbols for legibility. Twelve sighted, blindfolded adults completed the legibility task. Thirty-two symbols were produced in three sizes, varying in height from 0.64 cm and 1.27 cm, based on previous research. Several instances of each size of these symbols were mounted in rows on a display board. Systematically, a target symbol was presented to the participants at the bottom right of the display.

Participants were then asked to feel each symbol, row by row, and indicate whenever they reached a symbol identical to the target symbol. Omission and commission errors were recorded. In order to select a subset of legible symbols, the following criteria were applied: (a) at least 90% of the target symbols were identified, (b) at least 90% of participants identified at least 90% of the target symbols, and (c) no more than 5% of symbols were mistakenly identified as the target symbol. Using these criteria, the ideal size of each symbol was identified. When two or more sizes of the same symbol met all criteria, the smallest was chosen. In Study 2, the discriminability of this subset of symbols was evaluated using participants with visual impairments. Results suggested that all symbols met the criteria described above and thus were determined to be distinguishable from one another by both sighted blindfolded individuals and those with visual impairments.

Subsequent research by Rener (1993) provided an additional set of tactile symbols that are legible and discernible by individuals with visual impairments. The set of tactile symbols chosen for the current adaptation of the WISC-IV Coding measure were drawn from the set of legible symbols compiled by Lambert and Lederman (1989) and Rener (1993).

Number of symbols. The original WISC-IV Coding task includes nine distinct symbols as stimuli. In selecting the number of symbols to be included in the tactile adaptation, two considerations were made: (a) maintaining the task demands of the WISC-IV Coding task, and (b) ensuring that the number of symbols chosen did not influence legibility and discernibility.

Task demands. Based on decades of research on visual memory span, there is a great deal of evidence that the memory span of most adults is 7 ± 2 items (Miller, 1994). Given that the WISC-IV Coding task uses nine symbols, the task taxes visual memory capacity for children, whose memory span tends to be smaller than adults (Case, Kurland, & Goldberg, 1982). To ensure that the number of symbols included in the adaptation similarly taxed tactile memory capacity, research on tactile memory span was reviewed.

Early research comparing the visuospatial short-term memory of blind and sighted participants was completed by Cornoldi, Cortesi, and Preti (1991). In a sample of 20 congenitally blind adults and 20 sighted adults matched for age, sex, and education level, the researchers examined the relative capacity of tactile visuospatial memory. Tactile visuospatial memory was assessed by asking participants to follow a pathway through either two- or three-dimensional tactile matrices of increasing complexity. Participants were later asked to replicate the pathways. Results showed significantly poorer memory capacity for blind participants. In further analyses of group differences, it appeared that blind participants were using verbal mediation as a strategy, whereas blindfolded sighted participants were using visuospatial strategies to aid remembering. When blind participants were trained to use visuospatial strategies, performance improved, but was still not at the level of sighted participants. These results suggest that individuals with visual impairments may show poorer tactile visuospatial memory than sighted participants.

Currently, there is no extant research examining the capacity of tactile short term memory. Further, many tactile short-term memory tasks rely on the use of continuous movement or concurrent tactile presentation rather than discrete stimuli, making span calculations difficult. However, some general research on tactile short-term memory provides some preliminary evidence for the extent of tactile short-term memory capacity. In a sample of 32 blindfolded sighted undergraduate students, Nairne and McNabb (1985) demonstrated that, using strings of four tactile stimuli, participants showed chance level recollection (i.e., they performed at a level that is statistically equivalent to guessing). Given that participants showed near perfect recollection for strings of three tactile stimuli, this research suggests that four stimuli may tax tactile working memory capacity. Similarly, Bliss, Hewitt, Crane, Mansfield, and Townsend (1966) showed that, in a sample of sighted adults, the average number of tactile stimuli recalled ranged between 3.6 and 4.6, depending upon the task.

Although limited in scope, the research presented here suggests that tactile short-term memory capacity is more limited than visual or auditory short-term memory capacity. Further, using the results of studies with sighted participants to predict the tactile short term memory span of individuals with visual impairments may overestimate the true tactile short term memory span of individuals with visual impairments. Taken together, the studies described above suggest that tactile short term memory of sighted adults may range between 3 and 5 stimuli, and that adults

with visual impairments likely have smaller tactile working memory capacity than their sighted peers.

Number of symbols and legibility. In her comprehensive book on the topic of tactile graphics, Edman (1992) provided a coherent set of considerations and suggestions in the production of tactile graphics and tactile maps. With respect to the ideal number of symbols to be used in tactile graphics, Edman stated that children and adults with visual impairments experience more difficulties in discerning symbols in a display as the number of symbols used increases. Gill and James (1973) showed a linear increase in exploration time with each additional symbol used on a tactile map. Based on her data, including both exploration time and accuracy, Edman concluded that no more than five tactile symbols should be used to maximize discernibility and legibility. Because the adaptation was intended to tax memory capacity but not overwhelm legibility, a total of five symbols were selected for the tactile adaption of the WISC-IV Coding measure. The selected symbols are shown in Figure 2.

The Nature and Structure of Cognitive Abilities

In an effort to validate the adapted tactile processing speed instrument, convergent, concurrent, and divergent validity analyses are necessary. In order to determine which constructs may have hypothetical relationships with scores on the tactile processing speed instrument, research with sighted populations was consulted. As there is no available tactile processing speed measure, no studies to date have reported on the interrelationships between processing speed and other cognitive and academic abilities among individuals with visual impairments. Thus, the research reported below summarizes available research on the relationship between processing speed, other cognitive abilities, and academic achievement among sighted individuals.

Research in recent decades has suggested that human information processing abilities rely on limited processing resources (e.g., Kail, 1991; McGrew, 2005). Given these limited resources, individual differences in processing speed can influence how rapidly resources can be reallocated to new cognitive tasks, which has implications for memory, comprehension, and problem solving abilities (Flanagan et al., 2007). Woodcock (1993) used a valve metaphor to explain processing speed. Individuals with slow processing speed are similar to a water pipe in which the valve is partially closed, whereas individuals with fast processing speed are similar to a water pipe with a valve that is open wide. More information can enter the cognitive workspace of a child with fast processing speed, allowing a greater breadth of information to be remembered, comprehended, or acted upon.

Currently, the most empirically supported theory of intelligence is Cattell-Horn-Carroll (CHC) theory (Flanagan & Harrison, 2005; Flanagan et al., 2007; Mather & Le, 2002). CHC theory was originally put forth by McGrew (1997) and continues to be expanded upon and studied by McGrew and colleagues (e.g., McGrew, 2009; McGrew & Flanagan, 1998; Newton & McGrew, 2010; Taub & McGrew, 2004). CHC theory is a combination of two earlier theories of intelligence: Horn and Cattell's (1966) theory of fluid and crystallized intelligence, and Carroll's (1993) three-stratum theory of cognitive abilities.

CHC theory is based on the premise that
the structure of intelligence can be discovered by analyzing the interrelationship of scores on mental ability tests. To develop these models, large numbers of people are given many types of mental problems. The statistical technique of factor analysis is then

applied to the test scores to identify the factors or latent sources of individual differences in intelligence. (Davidson & Downing, 2000, p. 37)

Like Carroll's (1993) theory, CHC theory is a three-stratum theory of intelligence. Stratum III is the most general, representing *g* or general intelligence. Stratum II is more specific, representing between nine and 15 broad cognitive abilities such as short-term/working memory, fluid reasoning, or processing speed. Stratum I is the most specific, representing over 70 narrow cognitive abilities that are subordinate to the Stratum II broad abilities. The broad and narrow abilities included in CHC theory are a blend of those included in Cattell-Horn's (1966) and Carroll's theories, based upon those abilities that were most supported by McGrew and colleagues's factor analytic work (e.g., McGrew & Flanagan, 1998; Schneider & McGrew, 2012). CHC theory continues to be evaluated and expanded upon (e.g., Keith & Reynolds, 2010; Flanagan, Fiorello, & Ortiz, 2010). The most recent conceptualizations include between nine and 15 broad abilities and over 70 narrow abilities. Figure 1 depicts the most exhaustive and current version of CHC theory described by Schneider and McGrew (2012).

In CHC theory, all Stratum II abilities are intercorrelated (McGrew & Flanagan, 1998). Thus, processing speed is not important simply because it is included in these models and understood as a component of intelligence, but also because individual differences in processing speed are correlated with individual differences in other cognitive abilities. The following section provides a summary the relationship between processing speed and other areas of cognitive functioning.

The practical implications of individual differences in processing speed. Individual differences in processing speed have been correlated with many cognitive and academic skills. This section will review research on the relationship between processing speed and (a) CHC broad abilities, (b) general intelligence, and (c) academic achievement. For the purpose of consistency and based on effect size considerations (Cohen, 1988), correlations below .3 will be considered small, correlations between .3 *and* .5 will be considered moderate, and correlations above .5 will be considered large. The data presented here about the relationship of processing speed to CHC broad abilities and academic achievement will form the basis for validation of the adapted tactile processing speed measure.

Processing speed and specific CHC abilities. In a large scale review of 50 years of research on processing speed and its relationship to other aspects of intelligence, Sheppard and Vernon (2008) examined 192 studies that included measures of processing speed and at least one other area of CHC theory. Mean correlations between processing speed and fluid intelligence (*r* = .21) were stronger than correlations between processing speed and crystallized intelligence (*r* = .17), and the differences between these correlations were statistically significant, suggesting that individual differences in processing speed are more closely related to individual differences in novel problem solving abilities than accumulated knowledge. However, given the small differences between the two correlation coefficients, practical significance is questionable.

Research on age-related changes in fluid reasoning suggests that age-related declines in processing speed are correlated with age-related declines in fluid reasoning abilities across adulthood (Schretlen et al., 2000). Using a cross-sectional, hierarchical linear modeling approach to examine the scores of 197 adults between age 20 and 97 on measures of processing speed, working memory, and fluid reasoning, Schretlen and colleagues found a strong correlation between fluid reasoning and processing speed (*r* = .60). Whenever processing speed was

included in the model with all three variables, working memory showed a non-significant relationship with fluid reasoning ($r = .12$). Thus, although previous research has suggested that working memory is most predictive of age-related declines in fluid reasoning (Engle, Tuholski, Laughlin, & Conway, 1999), if processing speed is considered, the relationship between working memory and fluid reasoning is adults is not significant.

Among children, the influence of processing speed on fluid reasoning abilities has been termed a *developmental cascade* and a *bottleneck effect* (Fry & Hale, 1996, 2000). Fry and Hale's (1996, 2000) have suggested that there is a two-stage bottleneck or developmental cascade in the development of fluid reasoning abilities across childhood. In 1996, they found that processing speed was correlated with fluid reasoning ($r = .61$), as was working memory ($r = .64$). However, controlling for fluid reasoning abilities, Hale and Fry found that processing speed also influences the development of working memory capacity ($r = .55$), which in turn influences fluid reasoning. Thus, processing speed has both direct and indirect effects on fluid reasoning capacity throughout childhood. In their subsequent review of the literature, Fry and Hale (2000) found evidence across studies for this developmental cascade and the direct and indirect influence of processing speed on fluid reasoning across childhood.

Overall, the studies summarized above suggest that processing speed influences fluid reasoning across the lifespan. Influences appear to be most significant during childhood and late adulthood, likely owing to the age-related changes that occur in processing speed during these periods. During developmental periods wherein individual differences in processing speed are great, there is more evidence for a relationship between processing speed and fluid reasoning.

Other research shows evidence of small to moderate correlations between processing speed and other CHC areas such as crystallized intelligence (Bates & Shieles, 2000; Sheppard & Vernon, 2008), long-term retrieval (Brébion et al., 2000; Park et al., 1996; Poon & Fozard, 1978), visual perception (McGrew, 2009; Robinson & Sloutsky, 2007), and auditory perception (Deary, 1994; McGrew, 2009). However, the influence of processing speed on fluid reasoning and working memory has been examined most frequently in the research literature and moderate to strong correlations are found between processing speed and these two cognitive abilities.

Processing speed and general intelligence. General intelligence is synonymous with other constructs such as IQ, general cognitive ability, general mental ability, intelligence, or *g*. Some researchers argue that general intelligence is simply an artifact of the statistical methods used to understand and derive the correlations between cognitive tasks (e.g., Horn, 1985), whereas others argue that it is a latent variable that summarizes the overall cognitive functioning of an individual (e.g., Carroll, 1993). CHC theory includes general intelligence in its model of the structure of human intelligence. Research has shown that general intelligence scores are predictive of important life outcomes such as college graduation, employment, and overall health and longevity (e.g., Deary & Der, 2005; Gottfredson & Deary, 2004; Sewell & Shah, 1967; Wagner, 1997). Thus, despite the controversy, it appears to be important at least insofar as it is predictive of life outcomes.

In Sheppard and Vernon (2008)'s review, they found a small to moderate relationship between processing speed and general intelligence, ranging from .22 to .40 across studies. In an empirical study of paper and pencil processing speed measures and their correlations with general intelligence, Vigil-Colet and Codorniu-Raga (2002) found small to moderate relationships (from .17 to .33) between processing speed and general intelligence. Finally, in McGrew's factor analytic studies on the structure of intelligence, he consistently finds small to

moderate correlations between processing speed and general intelligence (McGrew, 2009; McGrew & Flanagan, 1998; Newton & McGrew, 2010; Taub & McGrew, 2004).

Processing speed and academic achievement. Although correlations between processing speed and CHC factors or general intelligence is a scientifically important and practically relevant finding, researchers have further sought to determine whether a relationship exists between processing speed and academic outcomes in key areas such as mathematics, reading, and writing.

Mathematics. Taub, Keith, Floyd, and McGrew (2008) analyzed the relationship between broad CHC abilities and mathematics achievement, using the standardization sample from the Woodcock-Johnson III Tests of Cognition and the Woodcock-Johnson III Tests of Academic Achievement (WJ-III). With a sample of 4649 children between ages 5 and 19 who completed each subtest on the WJ-III, the researchers used hierarchical linear modeling to answer questions about the interrelationship of cognitive and academic abilities. The only CHC areas with direct correlations with overall mathematics performance were processing speed, fluid reasoning, and crystallized intelligence. In keeping with previously reported research on the developmental trajectory of processing speed, it was most predictive of mathematics achievement for students below age 13 ($r = .38$). Fluid reasoning predicted mathematics achievement for students at all age levels ($.37 \leq r \leq .75$), and processing speed was likely indirectly implicated in this relationship.

In a more nuanced analysis of mathematics achievement and CHC factors, Floyd, Evans, and McGrew (2003) examined the influence of CHC factors on two different areas of math achievement: basic calculation skills and mathematical reasoning skills. Using the same sample as the study described above, the researchers completed two sets of analyses. Each set examined the relationships between eight broad CHC factors and either mathematics calculation skills or mathematics reasoning skills. According to their classification system, correlation coefficients between .10 and .29 were considered to be moderate and correlation coefficients above .30 were considered to be strong; exact correlation coefficients were not provided in the study. Processing speed was reported to have strong correlations (or, in our classification system, moderate correlations) with mathematics calculation skills between ages 7 and 15, and moderate correlations (or, in our classification system, small correlations) with mathematics reasoning skills in the same age span. These results suggest that processing speed is especially implicated in the ability to solve basic math problems, but that other cognitive skills contribute more to the ability to solve applied math problems.

Research on children with mathematical learning disabilities supports these results. Students with mathematical learning disabilities and poor processing speed tend to perform more poorly on basic arithmetic tasks than do students with mathematical learning disabilities with adequate processing speed (Geary, Hamson, & Hoard, 2000; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Hecht, Torgesen, Wagner, & Rashotte, 2001). Research with other samples has also supported a moderate, direct relationship between processing speed and mathematics computation skills ($r = .33$), but not algorithmic computation or applied problems (Fuchs et al., 2006). Path analyses reveal that processing speed may be implicated in higher-level mathematical processing through its influence on mathematics computation skills.

It is worth noting that these conceptualizations of mathematical cognition and the factors that contribute to successful mathematical problem solving are in contrast to ideas in the field of mathematics education. Mathematics education researchers generally focus on classroom level

9

variables such as engagement and high-level mathematical thinking and reasoning activities in understanding individual differences in mathematical problem solving success of students (e.g., Henningsen & Stein, 1997; Hiebert et al., 1996). Further, high levels of success in basic arithmetic skills are generally considered to be supportive, but not sufficient for mathematical problem solving in the classroom (National Research Council, 2001). Certainly, even among children with visual impairments, classroom-level variables influence the success of individual students in learning mathematical concepts. However, the focus of the current investigation is limited to the predictive power of cognitive variables in explaining academic success among children with visual impairments.

Reading. Some of the earliest work connecting broad CHC factors to academic achievement was conducted in the area of reading. Using the same WJ-III standardization sample and methods described in the mathematics section, Evans, Floyd, McGrew, and Leforgee (2002) analyzed the relationship between broad CHC factors and reading achievement between ages 2 and 95. Reading skills were measured in two areas: basic reading skills (i.e., decoding, sight word recognition), and reading comprehension. Processing speed was found to have a small correlation ($.10 \le r \le .29$) with both basic reading skills and reading comprehension between ages 6 and 10. The authors connected their findings to other work in early reading and academic skill acquisition, noting that fast processing speed will allow the automation of basic academic operations, allowing processing resources to be allocated to more complex aspects of the academic task.

Applying structural equation modeling to the same standardization sample, Benson (2008) examined the relationship between the reading fluency subtest on the WJ-III and broad CHC factors. He found evidence for an increase in correlation between processing speed and reading fluency across development, with a small correlation between kindergarten and third grade ($r = .22$), and strong correlations between fourth and sixth grade ($r = .59$) and seventh and twelfth grade ($r = .89$). This finding suggests that, as students become more automatic decoders, processing speed accounts for a larger portion of individual differences in reading fluency.

Other research has also explored the relationship between processing speed and reading skills with additional samples of children. With a sample of 279 children in third grade, Catts, Gillispie, Leonard, Kail, and Miller (2002) examined the relationship among general intelligence, processing speed, phonological awareness, and reading achievement. Using hierarchical linear modeling, when controlling for general intelligence and phonological awareness, processing speed continued to have a strong, statistically significant correlation with reading achievement in both basic reading skills ($R^2 = .531$) and reading comprehension ($R^2 = .549$).

Writing. Using the same WJ-III standardization sample and methods described in the mathematics section, Floyd, McGrew, and Evans (2008) examined the relationship between broad CHC factors and writing achievement between ages 7 and 18. Writing skills were measured in two areas: basic writing skills (i.e., spelling, punctuation), and written expression (i.e., the ability to fluently and clearly express ideas in writing). Processing speed had a moderate relationship with basic writing skills, and a strong relationship with written expression skills. Unlike in mathematics, wherein processing speed supports basic skills, in writing, processing speed supports fluent written expression. The authors suggested that this pattern exists because "the more rapidly an individual can automatize basic skills, the more attention and

memory resources can be allocated to higher-level aspects of task performance" (Floyd, McGrew, & Evans, 2008, p. 140). These findings are consistent with similar research conducted by McGrew and Knopik (1993) using the WJ-R.

Overall, the research on the relationship between processing speed and academic achievement indicates that processing speed has at least small correlations with all areas of reading, writing, and mathematics achievement. These correlations hold even when controlling for other cognitive variables known to correlate highly with these achievement areas. Given these findings, interventions and accommodations for children with poor processing speed may help to improve academic performance.

The Current Study

The goal of the current study was to evaluate the reliability and validity of scores obtained on the tactile adaptation of the WISC-IV Coding measure. Because the WISC-IV Coding measure is copyrighted, it cannot be presented here. However, Figure 3 presents a mock up of a similar task using different stimuli. Figure 4 presents the tactile adaptation, which was adapted according to the research findings summarized previously in the Measure Development section. In order to validate the adapted measure, a number of research questions were examined.

Reliability. Reliability refers to the consistency of scores on a measure. In the development and validation of any new measure, strong evidence of the reliability of scores on the measure is essential. It was hypothesized that there would be strong evidence ($\alpha > .9$) of the internal consistency of scores on the adapted tactile processing speed measure.

Validity. Validity refers to "the degree to which evidence and theory support the interpretations of test scores entailed by proposed uses of the test" (American Educational Research Association [AERA], American Psychological Association [APA], & National Council on Measurement in Education [NCME], 1999, p. 9). Essentially, validity analyses address the extent to which an instrument measures what it is intended to measure. Because there are several subtypes of validity, several validity analyses were completed.

Convergent validity. Convergent validity analyses address the extent to which scores on one instrument correlate with scores on an instrument that measures a similar constructs and related constructs. If scores on the adapted tactile processing speed measure correlate with scores on an established measure of speeded naming, this would provide support for convergent validity. It was hypothesized that there would be strong evidence ($r < -.5$) of convergent validity between the tactile processing speed measure and a measure of rapid automatic naming for braille letters and numbers. The anticipated correlation coefficient is a high negative number because low scores on the rapid automatic naming subtests are indicative of better performance, whereas high fluency scores on the tactile processing speed measure are indicative of better performance.

If scores on the adapted tactile processing speed measure correlate with scores on an established measure of fluid reasoning (i.e., the Blind Learning Aptitude Test), this would also provide evidence for convergent validity. Based on previous research with sighted samples, it was hypothesized that there would be moderate evidence (correlations between .3 and .5) of convergent validity between the adapted measure and a measure of fluid reasoning.

Further, based on research with sighted samples, one would expect evidence of concurrent validity not only with other cognitive measures, but also with measures of academic achievement. If scores on the adapted tactile processing speed measure correlate with scores on tests of reading fluency (i.e., braille DIBELS reading fluency) and math calculation skills (KeyMath-R braille edition Addition, Multiplication, and Mental Computation subtests), this would provide further evidence of convergent validity. Based on previous research, it was hypothesized that there would be strong evidence ($r > .5$) of convergent validity between scores on the tactile processing speed measure and DIBELS reading fluency, and KeyMath-R Addition, Multiplication, and Mental Computation.

Discriminant validity. Discriminant validity analyses help to determine whether two constructs that are supposed to be unrelated are unrelated. Because previous research has shown that processing speed is not well correlated with crystallized intelligence among sighted children, a measure of crystallized intelligence was selected for discriminant validity analyses. If scores on the tactile processing speed measure are not well correlated with scores on a measure of crystallized intelligence (i.e., WASI Vocabulary subtest), this would provide evidence of discriminant validity. Based on previous research with sighted samples, it was hypothesized that there would be a small correlation ($r < .3$) between scores on the two instruments.

With respect to tests of academic abilities, based on previous research with sighted samples, it was hypothesized that a Problem Solving test would show small correlations ($r < .3$) with scores on the tactile processing speed measure.

Method

Participants

Nineteen participants who use braille as their primary reading medium were recruited to take part in the study. The participants were in Grades 8–12 ($M_{age} = 15.74$ years, $SD = 2.20$ years, range: 13–21 years) in school in California ($n = 10$) or British Columbia ($n = 9$), on track to receive their high-school diplomas by age 22, and had no additional disabilities. Some participants had no visual function ($n = 10$), some could see light and/or light direction ($n = 3$), and some could detect the presence of large forms (e.g., a building; $n = 6$). The age of onset ranged from 0 years (congenital visual impairment) to 12 years of age, with a median age of onset of 0 years (i.e., at birth). The sample was evenly divided by gender, with 9 females and 10 males. Participant information is presented in Table 1. All participants and supervising guardians provided informed consent. The protocol was approved by the University of California, Berkeley's Committee for the Protection of Human Subjects.

Data Collection Procedures

All participants were tested by one of two examiners. Prior to beginning the study, the examiners practiced administering the tasks and agreed on test administration procedures. Verbal instructions (i.e., scripts) were included on each test record form to ensure consistency of administration across participants. Test sessions were video recorded and relevant participant responses were recorded on written test records.

Participants were tested outside of school hours, either at their school of residence, on the UC Berkeley campus, or in their home. On average, participants completed a total of 7 hours of individual testing with an examiner. Sessions were divided across multiple days, not exceeding 3 hours per day. Regular breaks were given between tasks and participants had the opportunity

to discontinue testing at any time. Tasks were counterbalanced across participants. Participants could not use a calculator, computer, or dictionary at any point during testing. On some tasks, participants could use a Perkins brailler (braille typewriter) or an abacus to solve math problems, as per task instructions.

To ensure that responses were recorded accurately on the test records, all responses were double checked for accuracy. Using the recorded video, each task was re-scored and/or re-timed. Any discrepancies were verified by an additional rater and discussed until agreement was reached.

Measures

To answer the research questions, a number of measures were administered to participants. These measures assess the broad CHC abilities of processing speed, crystallized intelligence, and fluid reasoning. Additional measures assess academic achievement in the areas of oral reading fluency and mathematics calculation and problem solving skills. The internal consistency of the scores on each instrument for the present sample is presented in the results section.

Tactile processing speed. The tactile processing speed task includes a key at the top of the page that pairs each of five tactile symbols with a braille number from one to five. Participants were instructed to examine this key and note the relationship between each symbol and number. Participants were then told to continue feeling down the page to the next row. This is the sample row. Participants were told that they may consult the key at the top of the page at any time during the sample or experimental trials. Participants were also told that the processing speed task is a timed task and that both accuracy and speed are important aspects of performance.

The symbols in the sample row are in random order, and participants were asked to state aloud the number that is associated with each symbol. If any mistakes were made, the instructions were re-stated and the sample row was completed again. Once the participants obtained 100% accuracy on the sample row, they were permitted to move on to the remaining rows. Participants were told to complete each item in order, from left to right, and to continue to the next row until they reached the end of the sheet. Participants were scored for both accuracy and total completion time. A photograph of the adapted tactile processing speed measure is shown in Figure 4.

Scoring for the tactile processing speed measure was completed in two ways. First, each participant's total correct responses on the full instrument were recorded. This score provides an index of the accuracy of responses. However, because the tactile processing speed instrument is intended to measure processing speed, a secondary score was devised. This score, called Tactile Processing Speed Fluency (TPSF), represents the total items completed correctly in a one minute span. This score is a fluency measure because it combines both accuracy and speed within a single metric.

Comprehensive Test of Phonological Processing. The Comprehensive Test of Phonological Processing (CTOPP) is a research-based assessment of phonological processing for children and young adults between age 5 and 24 (Wagner, Torgesen, & Rashotte, 1999). Based on several decades of research on the nature of phonological processing, the test includes two

subtests in each of three areas: phonological awareness, phonological memory, and rapid naming. Of interest to the current study are the rapid naming subtests.

Rapid naming subtests. Rapid naming refers to the ability to efficiently retrieve and state the label for a known symbol. In the case of the CTOPP, the child is presented with a series of letters or numbers and is asked to state aloud the label for each as quickly as possible. The CTOPP is designed for sighted students and all original stimuli are in print. According to the CTOPP Examiner's Manual, the reliability of the Rapid Letter Naming subtest scores for sighted individuals ranges from .77 to .92 for the ages included in the present study, with an average of .84. The reliability of the Rapid Digit Naming subtest scores for sighted individuals ranges from .86 to .93 for the ages included in the present study, with an average of .88. Because the participants in this project had visual impairments and were fluent braille readers, the stimuli in both subtests were transcribed into braille. No additional changes were made to stimuli or task administration. The rapid naming subtests may be considered measures of processing speed using familiar stimuli.

WASI vocabulary test. The Wechsler Abbreviated Scale of Intelligence (WASI; PsychCrop, 1999) is a short intelligence test designed to measure just two broad CHC abilities: fluid reasoning and crystallized intelligence. The vocabulary test is one of two subtests measuring crystallized intelligence. The participant was presented with a word and asked to define it. The participant's definition was compared to sample answers in the WASI scoring manual and given a score of 0, 1, or 2. If a participant's response did not clearly fit into one of the score categories, queries for further elaboration were made according to the WASI instructions. In the WASI scoring manual, the reported internal consistency of scores on the Vocabulary subtest with the standardization sample of children between ages 6 and 16 was .89 and the reported internal consistency for adults between ages 17 and 89 was .94.

Blind Learning Aptitude Test. The Blind Learning Aptitude Test (BLAT) was originally developed by Newland (1969) in response to the dearth of fluid reasoning measures that were accessible to students with visual impairments. It remains the only available test of fluid reasoning that is accessible to individuals who are blind. The BLAT includes five subtests. The first subtest requires the participant to examine a series of tactile shapes and identify the one that is different. The second subtest requires the participant to examine one tactile shape and then identify one that is identical among a set of five shapes. The third subtest is a tactile analogical reasoning test of the form A is to B as C is to __. For the third subtest, the participant was presented with a two by two grid of tactile shapes with the bottom right shape missing. The participant was then presented with four to six tactile shapes on the same page and asked which would best fit in the empty space in the grid to complete the analogy.

The fourth subtest is a part-whole test. For the fourth subtest, the participant was presented with a large shape with one piece missing and asked to select which of four to six tactile shapes would best complete the large shape. The fifth subtest is a tactile matrix reasoning test. For the fifth subtest, participants were shown a set of tactile information presented in three by three grid format, with one empty grid in the bottom right hand corner. Participants were then presented with six tactile shapes on the same page and asked which would best fit in the empty space in the grid to complete the matrix. In the original manual, the reported internal consistency

of the BLAT for 961 individuals with visual impairments who made up the standardization sample was .93. A sample item matrix reasoning item is presented in Figure 5.

DIBELS braille reading fluency. The Dynamic Indicators of Basic Early Reading Skills (DIBELS; Good & Kaminski, 2002) is a norm-referenced test of basic reading skills. Recently, the Dynamic Measurement Group, the developers of DIBELS, made a braille version of the stimuli available for purchase. However, the reliability and validity of the assessment tool scores were not re-evaluated using the braille stimuli with a group of braille-reading students. For the purpose of the current study, only one component of the DIBELS braille edition was administered to participants – the test of oral reading fluency. In the oral reading fluency task, participants were provided with a reading passage and were instructed to read aloud. Over a one minute span, errors and self-corrections were recorded on an examiner form. Total words read in the one minute span was also recorded. In order to maintain consistency across participants, a single grade level of DIBELS reading passages were selected. The highest level of reading passages available for DIBELS are at a sixth grade reading level. Because all participants had successfully completed sixth grade, and because all participants were successfully completing academic material well beyond a sixth grade level, the sixth grade DIBELS oral reading fluency passages were selected. All participants completed the oral reading fluency task using two DIBELS braille passages at the sixth grade level. The DIBELS braille reading fluency task may be considered a measure of academic achievement in reading fluency.

KeyMath-R Braille Adaptation. The KeyMath-R (Connolly, 1998) is a norm-referenced test of mathematics achievement across all domains of the K-12 mathematics curriculum. The test was originally produced in print form in 1998 and was subsequently adapted into braille and tactile graphics for students with visual impairments by the American Printing House of the Blind in 2004. All items that could be adapted according to best practices in braille transcription and tactile graphics production were adapted. Several items were eliminated from the test because they included visual language, concepts, or diagrams that could not validly be translated. The adapted version of the test was not re-normed with a sample of students with visual impairments. For the purpose of this study, four subtests in the area of mathematics calculation and problem solving were considered: Addition, Multiplication, Mental Computation, and Problem Solving. Both the Addition and Multiplication subtests include a page of braille mathematics problems and the participant may use a Perkins brailler (braille typewriter) or an abacus to help work through the problems.

These subtests may be considered tests of mathematics calculation skills. The Mental Computation subtest includes a verbal and braille presentation of mathematics problems. In this case, the participant may not use any materials to help solve the problems. Each problem must be solved within 15 seconds of presentation. This subtest may be considered a test of mathematics fluency. The Problem Solving subtest includes a set of word problems, sometimes with braille and/or tactile graphics. The participant must understand the word problem and apply mathematical strategies to produce a response. This test can be considered a test of mathematics problem solving.

Results
Because the assessment instruments selected for this project were adapted into braille (i.e., CTOPP Rapid Automatic Naming subtests), normed on groups of sighted students (i.e.,

DIBELS, KeyMath-R, WASI Vocabulary), or normed several decades ago (i.e., BLAT), preliminary analyses were completed to ensure that reliability of the instruments could be established for the present sample. For the purpose of this study, internal consistency (specifically, Cronbach's α) was calculated for each instrument. Based on previous research and standards in the field, an internal consistency above .90 is recommended for high stakes testing, whereas an internal consistency between .70 and .90 is considered adequate for low stakes testing (AERA, APA, & NCME, 1999).

The internal consistency of the CTOPP Rapid Automatic Naming subtests, the BLAT, the WASI Vocabulary subtest, the DIBELS Oral Reading Fluency passages, and the KeyMath-R Addition, Multiplication, Mental Computation, and Problem Solving subtests are reported in Table 2. As can be seen in this table, all subtests demonstrated adequate internal consistency at the .90 level, with the exception of the WASI Vocabulary subtest and two KeyMath-R subtests (Addition and Multiplication). All three of these subtests do not meet the .90 internal consistency necessary for high stakes testing, but demonstrate adequate internal consistency for low stakes testing. Given that this research study is not a high stakes endeavor, the lower internal consistency estimates were not considered problematic. However, given that many of these tests may be subsequently used for high stakes purposes such as psychoeducational evaluations of students with visual impairments, the more stringent .90 cutoff should be considered by practitioners.

Internal Consistency of the Tactile Processing Speed Measure

Internal consistency of the adapted tactile processing speed measure was calculated using two metrics of participant performance: accuracy on the full instrument, and Tactile Processing Speed Fluency (TPSF). TPSF represents the total correct items completed in a one-minute span. The rationale for computing TPSF for each participant is the nature of processing speed – tests of processing speed necessarily are measures of both speed and accuracy. Neither time nor accuracy alone can adequately capture participant performance on a test of processing speed.

In the current study, participants completed the full instrument in 65 to 537 seconds, with a median completion time of 89 seconds. With respect to accuracy, participants completed between 39 and 60 items correctly (out of a maximum 60 possible items), with a median accuracy of 58.5. The average chance of an accurate response to each item was .89. Using the Spearman-Brown formula, the internal consistency of accuracy scores on the full instrument was .93.

With respect to fluency, the range of computed TPSF scores was five to 56, with a median score of 36. Using the Spearman-Brown formula, the internal consistency of TPSF scores was .99. Because TPSF scores show a higher internal consistency and because these scores combine data on both accuracy and speed, TPSF scores were selected for subsequent validity analyses, although both are reported.

Validity

Validity analyses were completed by calculating simple correlation coefficients between TPSF and the other administered measures. Based on the total sample size ($N = 19$), any correlation coefficient above .455 or below -.455 is statistically significant (see Table 3). However, to compare students in British Columbia with students in California, validity analyses are also presented by geographic location (see Tables 4 and 5). For the California sample size (*n*

= 10), any correlation coefficient greater than |.633| is statistically significant. For the British Columbia sample size (*n* = 9), any correlation coefficient greater than |.667| is statistically significant. As can be seen, all significant correlations indicate a large effect size.

Convergent validity. Convergent validity analyses were completed using the TPSF/tactile processing speed accuracy scores and scores on the adapted CTOPP Rapid Letter Naming and Rapid Digit Naming subtests, the BLAT, the KeyMath-R Addition, Multiplication, and Mental Computation subtests, and the DIBELS.

CTOPP Rapid Letter Naming. Using the full sample, the correlation coefficient between CTOPP Rapid Letter Naming and TPSF scores was significant, as was the correlation coefficient between CTOPP Rapid Letter Naming scores and accuracy on the tactile processing speed measure. The negative coefficients indicate that low scores on the CTOPP subtest scores (i.e., fast rapid naming abilities) are associated with high TPSF scores (i.e., a greater number of symbols correctly identified in one minute). When considering the geographic subsamples, the accuracy scores were significantly related to CTOPP scores for the British Columbia sample only. No other correlation coefficient met criteria for significance.

CTOPP Rapid Digit Naming. Using the full sample, the correlation coefficient between CTOPP Rapid Digit Naming and the TPSF scores was not significant, nor was the correlation coefficient between CTOPP Rapid Digit Naming scores and accuracy scores on the tactile processing speed measure. When considering the geographic subsamples, no correlation coefficient met criteria for significance.

BLAT. Using the full sample, the correlation coefficient between BLAT and TPSF scores was significant, as was the correlation coefficient between BLAT scores and the tactile processing speed accuracy scores. When considering the geographic subsamples, the correlations involving TPSF scores, but not the accuracy scores, were significant for both the British Columbia and the California subsamples.

KeyMath-R Addition. Using the full sample, the correlation coefficient between the KeyMath-R Addition subtest scores and the TPSF scores was significant, as was the correlation between the KeyMath-R Addition subtest scores and the accuracy scores. When considering the geographic subsamples, both the TPSF and accuracy score correlations were significant in both British Columbia and California.

KeyMath-R Multiplication. Using the full sample, the correlation coefficient between the KeyMath-R Multiplication subtest scores and the TPSF scores was significant, as was the correlation coefficient between the KeyMath-R Multiplication subtest scores and the accuracy scores. When considering the geographic subsamples, both TPSF and accuracy score correlations were significant for the British Columbia sample, but both fell below significance for the California sample.

KeyMath-R Mental Computation. Using the full sample, the correlation coefficient between the KeyMath-R Mental Computation subtest scores and the TPSF scores was significant, as was the correlation coefficient between the KeyMath-R Mental Computation

subtest scores and the accuracy scores. When considering the geographic subsamples, the TPSF score was significantly correlated with the KeyMath-R Mental Computation subtest in both British Columbia and California, but the accuracy score was not significantly correlated with the KeyMath-R Mental Computation subtest in either subsample.

DIBELS. Using the full sample, the correlation coefficient between the DIBELS scores and the TPSF scores was not significant, nor was the correlation coefficient between the DIBELS scores and accuracy scores. However, when considering the geographic subsamples, the TSPF score was significantly correlated with DIBELS for the California sample. The accuracy score as not significantly correlated with the DIBELS for the California sample, nor were the TPSF and accuracy scores for the British Columbia sample.

Discriminant Validity. Discriminant validity analyses were completed using the TPSF/tactile processing speed accuracy scores and scores on WASI Vocabulary subtest and the KeyMath-R Problem Solving subtest.

WASI Vocabulary. Using the full sample, the correlation coefficient between the WASI Vocabulary subtest scores and TPSF scores was significant, as was the correlation coefficient between the WASI Vocabulary subtest scores and accuracy scores on the tactile processing speed measure. However, when considering geographic subsamples, neither correlation coefficient was significant for the California subsample. For the British Columbia subsample, the correlation coefficient for the WASI Vocabulary subtest and TPSF was significant, but the correlation coefficient for the WASI Vocabulary subtest and accuracy was not significant.

KeyMath-R Problem Solving. Using the full sample, the correlation coefficient between the KeyMath-R Problem Solving subtest scores and TPSF scores was significant, as was the correlation coefficient between the KeyMath-R Problem Solving subtest scores and accuracy scores on the tactile processing speed measure. However, when considering geographic subsamples, the correlation coefficient was significant for the KeyMath-R Problem Solving subtest and TPSF and accuracy for the British Columbia subsample. For the California sample, the correlation coefficient was significant for TPSF and KeyMath-R Problem Solving subtest, but not accuracy and KeyMath-R Problem Solving subtest.

Discussion

The goal of the current study was to describe the development of a tactile measure of processing speed and to provide preliminary validation data for the instrument. Because all extant measures of processing speed rely on visual stimuli, it has not been possible to measure this important cognitive ability among individuals with visual impairments. In an effort to provide preliminary validation data for the instrument described in this study, reliability and validity analyses were undertaken.

Reliability

Reliability of related measures. Prior to determining the internal consistency of scores on the adapted measure of interest, internal consistency analyses were conducted for all other administered measures. This was a necessary first step in the analyses because the instruments included in this study were either not normed using a sample of individuals with visual

impairments (e.g., KeyMath-R, DIBELS, WASI), were normed over four decades ago (e.g., BLAT), or were adapted into braille for the purpose of this research (e.g., CTOPP Rapid Automatic Naming subtests). As is outlined in Table 2, scores on all instruments reached the .90 alpha threshold for internal consistency, with the exception of the WASI Vocabulary subtest and the KeyMath-R Addition and Multiplication subtests.

Of particular note is the relatively low internal consistency of scores on the WASI Vocabulary subtest for participants in the current study. This subtest demonstrates adequate internal consistency with the original sighted norming group, suggesting that the instrument may not be functioning appropriately for individuals with visual impairments. The majority of the sample indicated that they had been visually impaired from birth or from a very early age and based on previous research (e.g., Wilton, 2011) language and conceptual development can be significantly impacted among individuals who experience early visual impairment. Given that the WASI Vocabulary subtest is part of an established intelligence battery, and given that verbal intelligence tests are among the only tests administered to students with visual impairments by practicing school psychologists (e.g., Bauman & Kropf, 1979; Crepeau-Hobson & Vujeva, 2012), evidence of inadequate internal consistency is problematic. Future work should include a wider range of ages and ability levels to determine whether this finding is replicated in a larger sample of individuals with visual impairments.

Internal consistency of the tactile processing speed measure. The internal consistency of scores on the tactile processing speed measure was calculated in two ways. The first analysis used accuracy data for each participant on the full instrument and the second analysis used fluency data for each participant. A new metric, TPSF, was generated to account for fluency (i.e., a combination of accuracy and speed) on the instrument. Based on standards in the field of measurement, the internal consistency estimates for both metrics are indicative of excellent reliability (AERA, APA, & NCME, 1999). Because this instrument may be used in high-stakes decision making contexts such as psychoeducational evaluations, measurement experts suggest that reliability of .90 is the minimum to be tolerated and reliabilities of .95 should be the desired standard in these contexts (Ary, Jacobs, Razavieh, & Sorensen, 2006).

Validity
Convergent validity. The tactile processing speed instrument is intended to measure processing speed for tactile stimuli. Thus, correlation with another measure of processing speed (specifically, speeded naming) was necessary. Although no such tools currently exist, the CTOPP contains two speeded naming subtests that could easily be adapted into an accessible format by transcribing the printed letters and numbers into braille. Internal consistency analyses suggested that the adapted speeded naming measures had excellent reliability. Although the correlation coefficient between the CTOPP Rapid Letter Naming and TPSF/accuracy scores fell within the hypothesized range, the correlation coefficients between CTOPP Rapid Digit Naming and TPSF/accuracy scores did not. This finding indicates good convergent validity with at least one measure of rapid automatic naming for braille.

Given that the CTOPP Rapid Naming subtests and the tactile processing speed measure are both intended to measure speeded naming abilities, a strong correlation was hypothesized. However, compared to other correlation coefficients reported in the results section, the correlation coefficients representing relationships between the CTOPP Rapid Naming subtests and the tactile processing speed measure were among the lowest. A potential explanation for this

result relates to the content of both instruments. Although both are speeded naming tests, the tactile processing speed instrument requires participants to learn the relationship between novel symbols and their labels, whereas the CTOPP subtests simply require the participant to provide the label for overlearned stimuli (i.e., letters and numbers). Thus, the CTOPP Rapid Naming subtests were likely simpler exercises for participants, as no novel learning took place in the completion of the task. The novel learning required to successfully complete the tactile processing speed instrument may have required skills beyond simple speeded naming, leading to a relatively low correlation coefficient when comparing scores on these instruments.

Further analyses of convergent validity relied on hypothesized relationships between processing speed and other cognitive skills (i.e., fluid reasoning) and academic skills (i.e., oral reading fluency, math fluency, and basic arithmetic skills). To determine whether scores on the processing speed instrument are related to scores on a measure of tactile fluid reasoning, correlation coefficients were calculated. The correlation coefficient for both accuracy and TSPF scores and the BLAT total score was high ($r > .5$) and statistically significant. Based on research with sighted samples and CHC theory, this relationship was expected.

However, the strength of the relationship between TPSF scores and BLAT scores was greater than expected based on research with sighted samples. It was hypothesized that there would be evidence of a moderate correlation between processing speed and fluid reasoning abilities in the current sample, but results demonstrated a strong correlation. A potential explanation for this finding relates to the concept of *g*. As described in the introduction, *g* is a latent construct, purportedly representing the general intelligence of an individual. Based on factor analyses, research has demonstrated that certain broad CHC abilities (i.e., crystallized intelligence and fluid intelligence) have stronger relationships with *g* than others (Colom, Jung, & Haier, 2006), and that certain subtests are more *g*-loaded than others (i.e., some subtests have higher correlations with the *g* factor). Since the BLAT is a measure of fluid reasoning, it is likely that it has high *g* loading. Indeed, validity analyses with the original norming sample of the BLAT suggest a correlation of .73 between BLAT total score and verbal IQ on the original WISC and a correlation of .75 between the BLAT total score and the verbal IQ on the Hayes-Binet (Newland, 1969). Because the tactile processing speed measure has a learning component that is not always present in processing speed measures (e.g., the CTOPP Rapid Automatic Naming subtests do not require learning new symbol-referent relations), it too may have more *g* loading than other processing speed measures. This potential *g* loading may help to explain the stronger than expected correlations between the TSPF scores and the BLAT scores.

To determine whether scores on the tactile processing speed instrument are related to oral reading fluency scores, correlation coefficients were calculated. The correlation coefficients were in the moderate, but non-significant range ($.3 < r < .5$) when considering the full sample of participants. However, there was significant variability between geographic subsamples. Although there was a strong correlation between tactile processing speed and oral reading fluency in the California subsample, there was a low correlation coefficient in the British Columbia sample. Given that British Columbia participants indicated that they did not currently use braille regularly in language arts activities at school (these participants instead rely on computers presenting an audio output of electronic versions of textbooks, teacher notes, and the like), this finding is not surprising. These findings suggest that, as among sighted samples, braille reading fluency is correlated with processing speed among a sample of individuals with visual impairments. However, this relationship appears to be stronger among individuals who regularly read braille rather than those who rely on technology for literacy activities. This

difference suggests that regular, current experience reading may moderate the relationship between processing speed and reading fluency. That is, individuals with fast processing speed will likely be more fluent readers *if and only if* they read regularly. Simply having fast processing speed does not increase reading fluency without practice in reading.

To determine whether scores on the tactile processing speed instrument were related to mathematics fluency and basic arithmetic skills, correlation coefficients were calculated. Correlation coefficients for all three KeyMath-R subtests (Addition, Multiplication, and Mental Computation) were high ($r > .5$) and significant. These results suggest that, as in sighted samples, processing speed is correlated with mathematics calculation skills on timed and untimed tests of simple arithmetic. However, the inadequate internal consistency of the Addition and Multiplication subtests should be considered in interpreting the correlation coefficients reported here. If those two subtests are eliminated from consideration, the correlation coefficients between ? and Mental Computation scores subtest suggest that scores on a measure of timed simple arithmetic skills is strongly related to processing speed for the participants in the sample.

Discriminant validity. Because previous research has shown that processing speed is not well correlated with crystallized intelligence among sighted children, a low correlation ($r < .3$) was anticipated between these two constructs. To evaluate this hypothesis, a correlation coefficient was calculated to determine the relationship between scores on the tactile processing sped measure and scores on the WASI Vocabulary subtest. The correlation coefficient fell in the high range. This outcome is in direct contrast to research with sighted samples, where processing speed and crystallized intelligence show relatively low correlations. However, the poor internal consistency of the WASI Vocabulary subtest for the current sample suggests that these correlations should be interpreted with caution. Poor internal consistency may suggest that the construct of interest (crystallized intelligence) may not be reliably measured by the WASI Vocabulary subtest. As such, the correlation coefficients reported here may not represent the actual relationship between crystallized intelligence and processing speed for the sample.

Further, because previous research has not established a relationship between mathematics problem solving skills and processing speed among sighted children, a low correlation was anticipated between these two constructs. To evaluate this hypothesis, a correlation coefficient was calculated to determine the strength of the relationship between scores on the tactile processing speed measure and the KeyMath-R Problem Solving subtest. The correlation coefficient fell in the high range. A potential explanation for this finding relates to previous work with sighted populations that suggests that adequate processing speed is a necessary developmental prerequisite to successful higher level problem solving skills on tests of fluid reasoning (Fry & Hale, 1996, 2000). Better processing speed may be correlated with better math problem solving abilities among the sample because processing speed can be a necessary cognitive underpinning of successful higher order problem solving across domains. Another potential explanation relates to the potential *g* loading of the tactile processing speed measure. If it is a highly *g*-loaded measure, it is likely that it will show higher than expected correlations with applied, complex measures of academic achievement such as problem solving in mathematics.

Based on the correlation between scores on the tactile processing speed measure and both WASI Vocabulary and KeyMath-R Problem Solving, no conclusion can be reached regarding the divergent validity of the tactile processing speed measure. Future work should employ

another measure of crystallized intelligence to determine whether evidence of divergent validity can be established.

Implications

Aside from the specific goal of describing and validating an adapted tactile measure of processing speed, the goal of the current study was to address larger questions about cognitive abilities among individuals with visual impairments. Because psychoeducational evaluations are legally mandated triennially for any student in the United States with a disability, students with visual impairments are expected to receive a full evaluation by a school psychologist every three years of their K-12 academic career. However, the majority of assessment tools are inaccessible to students with visual impairments, making complete psychoeducational evaluations impossible. Although no prior attempts have been made to design accessible assessment tools for processing speed among individuals with visual impairments, the current study puts forth preliminary data suggesting that processing speed can be reliably and validly measured in this population.

Aside from legal implications, the ability to provide a child's special education team with reliable and valid information regarding processing speed can help guide the team in designing appropriate goals, services, and interventions for the student. A student with very poor processing speed may have mathematics goals that focus more on building problem solving strategies that allow the child to slowly think through the solution for a problem. The ability to design individualized programs based on individual student data is the cornerstone of special education, and the ability to accurately measure processing speed among students with visual impairments is a first step in that direction.

Limitations

Like all research, the study described in this paper has a number of limitations. The primary limitation of the research is the small sample size. Although visual impairment is a very low incidence disability and a sample of 19 participants is comparable relative to other recent empirical work with individuals with visual impairments (e.g., Oshima, Arai, Ichihara, & Nakano, 2014), a sample of this size limits the types of statistical analyses that can be completed. For example, multiple linear regression (with two or more predictors) analyses were not possible, limiting the ability to determine the relative contribution of two or more measured abilities on an outcome measure of interest.

Another important limitation of this research relates to the exclusionary criteria for the sample. For the purpose of these preliminary analyses, strict exclusionary criteria were selected for the current study. These exclusionary criteria related to the participant's age (between 13 and 22 years of age), academic track (eligible and on track to graduate from high school by age 22), familiarity with braille, and the presence of additional disabilities (no additional disabilities). However, if the tool is eventually to be used by practicing psychologists, it will need to be validated with a larger and more diverse sample that is representative of the full spectrum of individuals with visual impairments. Recent work has suggested that multiple disabilities are more common than not among individuals with visual impairments (Hatton, Ivy, & Boyer, 2013) and that fewer students rely on braille as their literacy medium (Clunies-Ross, 2005). Thus, the applicability of the current findings to the full population of individuals with visual impairments is questionable given the exclusionary criteria used for establishing the sample.

Another limitation of the current study is the availability of accessible, valid tools measuring related constructs of interest. Although test publishers have made some attempts to

adapt materials into formats that are accessible to individuals with visual impairments (e.g., KeyMath-R braille adaptation and DIBELS braille oral reading fluency), these attempts have generally not included re-norming and/or re-validating use of the instrument with individuals with visual impairments. As was apparent on two of the four KeyMath-R subtests under investigation, internal consistency estimates were below accepted thresholds for high stakes testing, suggesting that the adaptation may not be functioning appropriately for individuals with visual impairments. Further, a verbal test (e.g., WASI Vocabulary subtest) that has been used for decades to assess the verbal/crystallized intelligence of individuals with visual impairments (Bauman & Kropf, 1979; Crepeau-Hobson & Vujeva, 2012) appears to lack adequate internal consistency in the current sample. These psychometric shortcomings are concerning both for research and applied purposes, as they call into question whether these instruments are appropriate to use with individuals with visual impairments. As in this research, the ability to validate a novel instrument depends on convergent, concurrent, and divergent validity analyses with other established measures. With such a limited set of established measures that have been validated for individuals with visual impairments, validity studies are difficult to conduct.

Future Directions

To provide additional support for the reliability of scores on the tactile processing speed instrument, future work should seek to evaluate the test-retest reliability of the instrument. Internal consistency provides only preliminary evidence of reliability and additional administrations for each participant would help to support the reliability of the instrument across time. It may also be necessary to correlate performance on the adapted tactile instrument with performance on the original WISC-IV Coding instrument among a sample of blindfolded sighted adolescents to determine convergent validity. A study of this type could help to establish whether the tactile processing speed measure and the WISC-IV Coding measure are measuring similar constructs. However, previous theorists have warned against using blindfolded sighted participants in such analyses because participants with visual impairments may engage in qualitatively different types of cognitive processing to complete the task, making such comparisons invalid (Warren, 1994).

To provide additional support for the convergent validity of scores on the instrument, additional tests of cognitive abilities should be administered, preferably covering all areas of CHC theory. This type of research would help to evaluate whether patterns of relationships between processing speed and other cognitive abilities that are noted among sighted individuals are present among individuals with visual impairments.

Finally, to provide support for the divergent validity of scores on the instrument, additional measures of crystallized intelligence should be administered. Because the WASI Vocabulary subtest does not demonstrate adequate internal consistency for the present sample, other crystallized intelligence measures will be necessary to establish divergent validity in future research. Further, additional areas of cognitive and/or academic skills that show small correlations with processing speed among sighted samples should be included to provide additional support for divergent validity.

If research continues to support the reliability and validity of the instrument, future work should involve significantly larger samples to develop norms for performance on the task. These norms will allow for the practical use of the instrument by psychologists and other educational professionals in determining whether an individual with a visual impairment has sub-average, average, or above average processing speed for their age. Future samples should also include

less restrictive exclusionary criteria to ensure that the instrument is applicable to individuals with visual impairments who are low functioning and/or who have additional disabilities.

References

American Educational Research Association, American Psychological Association, National Council on Measurement in Education, Joint Committee on Standards for Educational, & Psychological Testing (1999). *Standards for Educational and Psychological Testing.* Washington, DC: American Educational Research Association.

Ary, D., Jacobs, L. C., Razavieh, A., & Sorensen, C. (2010). *Introduction to research in education*. New York, NY: Cengage Learning.

Bates, T. C., & Shieles, A. (2003). Crystallized intelligence as a product of speed and drive for experience: the relationship of inspection time and openness to g and Gc. *Intelligence*, *31*, 275–287. doi:10.1016/S0160-2896(02)00176-9

Bauman, M. K., & Kropf, C. A. (1979). Psychological tests used with blind and visually handicapped persons. *School Psychology Review, 8,* 257–270.

Benson, N. (2008). Cattell-Horn-Carroll cognitive abilities and reading achievement. *Journal of Psychoeducational Assessment, 26*, 27–41. doi:10.1177/0734282907301424

Bliss, J. C., Crane, H. D., Mansfield, P. K., & Townsend, J. T. (1966). Information available in brief tactile presentations. *Perception & Psychophysics*, *1*, 273–283. doi:10.3758/BF03207391

Brébion, G., Smith, M. J., Gorman, J. M., Malaspina, D., Sharif, Z., & Amador, X. (2000). Memory and schizophrenia: differential link of processing speed and selective attention with two levels of encoding. *Journal of Psychiatric Research*, *34*, 121–127. doi:10.1016/S0022-3956(99)00050-3

Carroll, J. B. (1993). *Human cognitive abilities*. Cambridge, UK: Cambridge University Press.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of experimental child psychology, 33*, 386–404. doi:10.1016/0022-0965(82)90054-6

Catts, H. W., Gillispie, M., Leonard, L. B., Kail, R. V., & Miller, C. A. (2002). The role of speed of processing, rapid naming, and phonological awareness in reading achievement. *Journal of learning disabilities, 35*, 510–525. doi:10.1177/00222194020350060301

Chiaravalloti, N. D., Christodoulou, C., Demaree, H. A., & DeLuca, J. (2003). Differentiating simple versus complex processing speed: Influence on new learning and memory performance. *Journal of Clinical and Experimental Neuropsychology, 25,* 489–501. doi:10.1076/jcen.25.4.489.13878

Clunies-Ross, L. (2005). Windows of perception: A review of the literature concerning uncontracted and contracted literary braille. *British Journal of Visual Impairment, 23,* 67–74. doi:10.1177/0264619605054778

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). New York, NY: Lawrence Erlbaum Associates.

Colom, R., Jung, R. E., & Haier, R. J. (2006). Distributed brain sites for the *g*-factor of intelligence. *Neuroimage*, *31*, 1359–1365. doi:10.1016/j.neuroimage.2006.01.006

Connolly, A. J. (1998). *KeyMath—Revised Normative Update: A diagnostic inventory of essential mathematics*. Circle Pines, MN: American Guidance Service.

Cornoldi, C., Cortesi, A., & Preti, D. (1991). Individual differences in the capacity limitations of visuospatial short-term memory: Research on sighted and totally congenitally blind people. *Memory & Cognition*, *19*, 459–468. doi:10.3758/BF03199569

Crepeau-Hobson, F., & Vujeva, H. (2012). Assessment of cognitive ability of students with severe and low-incidence disabilities: Part 2. *Communique*, *41*(3), 4–6.

Davidson, J. E., & Downing, C. L. (2000). Contemporary models of intelligence. In R. J. Sternberg (Ed.), *Handbook of intelligence* (34–49). Cambridge, UK: Cambridge University Press.

Deary, I. J. (1994). Intelligence and auditory discrimination: Separating processing speed and fidelity of stimulus representation. *Intelligence*, *18*, 189–213. doi:10.1016/0160-2896(94)90027-2

Deary, I. J., & Der, G. (2005). Reaction time explains IQ's association with death. *Psychological Science*, *16*, 64–69. doi:10.1111/j.0956-7976.2005.00781.x

DeLuca, J., & Kalmar, J. H. (2008). *Information processing speed in clinical populations*. New York, NY: Taylor and Francis.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333,* 959–964. doi:10.1126/science.1204529

Dye, M. W. G., Green, C. S., & Bavelier, D. (2009). Increasing speed of processing with action video games. *Current Directions in Psychological Science, 18,* 321–326. doi:10.1111/j.1467-8721.2009.01660.x

Edman, P. (1992). *Tactile graphics*. Louisville, KY: AFB press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128,* 309–323. doi:10.1037//0096-3445.128.3.309

Edwards, J. D., Wadley, V. G., Myers, R. S., Roenker, D. L., Cissell, G. M., & Ball, K. K. (2002). Transfer of a speed of processing intervention to near and far cognitive functions. *Gerontology*, *48*, 329–340. doi:10.1159/000065259

Evans, J. J., Floyd, R. G., McGrew, K. S., & Leforgee, M. H. (2002). The relations between measures of Cattell-Horn-Carroll (CHC) cognitive abilities and reading achievement during childhood and adolescence. *School Psychology Review*, *31*, 246–262.

Flanagan, D. P., Fiorello, C. A., & Ortiz, S. O. (2010). Enhancing practice through application of Cattell–Horn–Carroll theory and research: A "third method" approach to specific learning disability identification. *Psychology in the Schools*, *47*, 739–760. doi:10.1002/pits.20501

Flanagan, D. P., & Harrison, P. L. (2005). *Contemporary intellectual assessment: Theories, tests, and issues*. New York, NY: Guilford Press.

Flanagan, D. P., Ortiz, S. O., & Alfonso, V. C. (2007). *Essentials of cross-battery assessment*. New York, NY: John Wiley & Sons.

Floyd, R. G., Evans, J. J., & McGrew, K. S. (2003). Relations between measures of Cattell‐Horn‐Carroll (CHC) cognitive abilities and mathematics achievement across the school‐age years. *Psychology in the Schools*, *40*, 155–171. doi:10.1002/pits.10083

Floyd, R. G., McGrew, K. S., & Evans, J. J. (2008). The relative contributions of the Cattell‐Horn‐Carroll cognitive abilities in explaining writing achievement during childhood and adolescence. *Psychology in the Schools*, *45*, 132–144. doi:10.1002/pits.20284

Fry, A. F., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science*, *7*, 237–241. doi:10.1111/j.1467-9280.1996.tb00366.x

Fry, A. F., & Hale, S. (2000). Relationships among processing speed, working memory, and fluid intelligence in children. *Biological psychology*, *54*, 1–34. doi:10.1016/S0301-0511(00)00051-X

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (2008). *Cognitive Neuroscience.* New York, NY: W. W. Norton & Company.

Geary, D. C., Hamson, C. O., & Hoard, M. K. (2000). Numerical and arithmetical cognition: A longitudinal study of process and concept deficits in children with learning disability. *Journal of Experimental Child Psychology*, *77*, 236–263. doi:10.1006/jecp.2000.2561

Geary, D. C., Hoard, M. K., Byrd‑Craven, J., Nugent, L., & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development*, *78*, 1343–1359. doi:10.1111/j.1467-8624.2007.01069.x

Gill, J. M., & James, G. A. (1973). A study on the discriminability of tactual point symbols. *American Foundation for the Blind Research Bulletin*, *26*, 19–34.

Good, R. H., & Kaminski, R. (2002). Dynamic Indicators of Basic Early Literacy Skills (6th ed.). Eugene, OR: Institute for the Development of Education Achievement.

Gottfredson, L. S., & Deary, I. J. (2004). Intelligence predicts health and longevity, but why? *Current Directions in Psychological Science*, *13*, 1–4. doi:10.1111/j.0963-7214.2004.01301001.x

Hatton, D. D., Ivy, S. E., & Boyer, C. (2013). Severe visual impairments in infants and toddlers in the United States. *Journal of Visual Impairment & Blindness, 107,* 325–336.

Hecht, S. A., Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *Journal of Experimental Child Psychology*, *79*, 192–227. doi:10.1006/jecp.2000.2586

Henningsen, M., & Stein, M. K. (1997). Mathematical tasks and student cognition: Classroom-based factors that support and inhibit high-level mathematical thinking and reasoning. *Journal for Research in Mathematics Education, 28,* 524–549.

Hiebert, J., Carpenter, T. P., Fennema, E., Fuson, K., Human, P., Hanlie, M., … Wearne, D. (1996). Problem solving as a basis for reform in curriculum and instruction: The case of mathematics. *Educational Researcher, 25,* 12–21. doi:10.3102/0013189X025004012

Horn, J. L. (1985). Remodeling old models of intelligence. *Intelligence*, *3*, 229–239.

Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of educational psychology*, *57*, 253–270.

Jensen, A. R. (2006). *Clocking the mind: Mental chronometry and individual differences.* New York, NY: Elsevier Science

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin*, *109*, 490–501. doi:10.1037//0033-2909.109.3.490

Keith, T. Z., & Reynolds, M. R. (2010). Cattell–Horn–Carroll abilities and cognitive tests: What we've learned from 20 years of research. *Psychology in the Schools*, *47*, 635–650. doi:10.1002/pits.20496

Lederman, S. J., & Lambert, L. M. (1989). An evaluation of the legibility and meaningfulness of potential map symbols. *Journal of Visual Impairment & Blindness*, *83,* 397–403.

Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A., & Sweeney, J. A. (2004). Maturation of cognitive processes from late childhood to adulthood. *Child Development, 75,* 1357–1372.doi:10.1111/j.1467-8624.2004.00745.x

Mackey, A. P., Hill, S. S., Stone, S. I., & Bunge, S. A. (2011). Differential effects of reasoning and speed training in children. *Developmental Science*, *14*, 582–590. doi:10.1111/j.1467-7687.2010.01005.x

Martin, T. A., & Bush, S. S. (2008). Assessment tools and research methods for human information processing speed. In J. DeLuca & J. H. Kalmar (Eds.), *Information processing speed in clinical populations* (pp. 29–51). City, ST: Publisher.

Mather, N., & Jaffe, L. E. (2002). *Woodcock-Johnson III: Reports, Guidelines and Recommendations*. New York, NY: Wiley.

McGrew, K. S. (1997). Analysis of the major intelligence batteries according to a proposed comprehensive Gf-Gc framework. In D. P. Flanagan, J. L. Genshaft, and P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (pp. 151–179). New York, NY: The Guilford Press.

McGrew, K. S. (2005). The Cattell-Horn-Carroll theory of cognitive abilities: Past, present, and future. In D. P. Flanagan, J. L. Genshaft, & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (2nd ed., pp.136–182). New York. NY: Guilford.

McGrew, K. S. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence*, *37*, 1–10. doi:10.1016/j.intell.2008.08.004

McGrew, K. S., & Flanagan, D. P. (1998). *The intelligence test desk reference: Gf-Gc cross-battery assessment*. New York, NY: Allyn & Bacon.

McGrew, K. S., & Knopik, S. N. (1993). The relationship between the WJ-R Gf-Gc cognitive clusters and writing achievement across the life-span. *School Psychology Review, 22,* 687–695.

Miller, G. A. (1994). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 101*, 343–352. doi:10.1037//0033-295X.101.2.343

Nairne, J. S., & McNabb, W. L. (1985). More modality effects in the absence of sound. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *11*, 596–604. doi:10.1037//0278-7393.11.3.596

National Research Council. (2001). *Adding it up: Helping children learn mathematics*. Washington, DC: The National Academies Press.

Newland, T. E. (1969). *The Blind Learning Aptitude Test.* Washington, DC: Office of Education, Bureau of Research.

Newton, J. H., & McGrew, K. S. (2010). Introduction to the special issue: Current research in Cattell–Horn–Carroll–based assessment. *Psychology in the Schools*, *47*, 621–634. doi:10.1002/pits.20495

Nouchi, R., Taki, Y., Takeuchi, H., Hashizume, H., Akitsuki, Y., Shigemune, Y., ... & Kawashima, R. (2012). Brain training game improves executive functions and processing speed in the elderly: A randomized controlled trial. *PloS one*, *7*, e29676. doi:10.1371/journal.pone.0029676

Oshima, K., Arai, T., Ichihara, S., & Nakano, Y. (2014). Tactile sensitivity and braille reading in people with early and late blindness. *Journal of Visual Impairment and Blindness, 108*, 122–132.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., ... & Ballard, C. G. (2010). Putting brain training to the test. *Nature*, *465*, 775–778. doi:10.1038/nature09042

Park, D. C., Smith, A. D., Lautenschlager, G., Earles, J. L., Frieske, D., Zwahr, M., & Gaines, C. L. (1996). Mediators of long-term memory performance across the life span. *Psychology and Aging*, *11*, 621–637. doi:10.1037//0882-7974.11.4.621

Poon, L. W., & Fozard, J. L. (1978). Speed of retrieval from long-term memory in relation to age, familiarity, and datedness of information. *Journal of Gerontology*, *33*, 711–717. doi:10.1093/geronj/33.5.711

PsychCorp (1999). *WASI manual.* San Antonio, TX: Harcourt Assessment, Inc.

Rener, R. (1993). Tactile cartography: Another view of tactile cartographic symbols. *The Cartographic Journal, 30*, 195–198. doi:10.1179/000870493787860139

Robinson, C. W., & Sloutsky, V. M. (2007). Visual processing speed: Effects of auditory input on visual processing. *Developmental Science*, *10*, 734–740. doi:10.1111/j.1467-7687.2007.00627.x

Salthouse, T. A. (1996). The processing speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428. doi:10.1037//0033-295X.103.3.403

Sattler, J. M. (2008). *Assessment of children: Cognitive foundations.* San Diego, CA: Jerome M. Sattler Publications.

Schneider, W. J., & McGrew, K. S. (2012). The Cattell-Horn-Carroll model of intelligence. In D. P. Flanagan, & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and, issues* (3rd ed., pp. 99-144). New York, NY: Guilford.

Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A., & Barta, P. (2000). Elucidating the contributions of processing speed, executive ability, and frontal lobe volume to normal age-related differences in fluid intelligence. *Journal of the International Neuropsychological Society*, *6*, 52–61. doi:10.1017/S1355617700611062

Sewell, W. H., & Shah, V. P. (1967). Socioeconomic status, intelligence, and the attainment of higher education. *Sociology of Education*, 1–23. doi:10.2307/2112184

Sheppard, L. D., & Vernon, P. A. (2008). Intelligence and speed of information-processing: A review of 50 years of research. *Personality and Individual Differences*, *44*, 535–551. doi:10.1016/j.paid.2007.09.015

Taub, G. E., Keith, T. Z., Floyd, R. G., & McGrew, K. S. (2008). Effects of general and broad cognitive abilities on mathematics achievement. *School Psychology Quarterly*, *23*, 187–198. doi:10.1037/1045-3830.23.2.187

Taub, G. E., & McGrew, K. S. (2004). A confirmatory factor analysis of Cattell-Horn-Carroll Theory and cross-age invariance of the Woodcock-Johnson Tests of Cognitive Abilities III. *School Psychology Quarterly*, *19*, 72–87. doi:10.1521/scpq.19.1.72.29409

Vigil-Colet, A., & Codorniu-Raga, M. J. (2002). How inspection time and paper and pencil measures of processing speed are related to intelligence. *Personality and Individual Differences*, *33*, 1149–1161. doi:10.1016/S0191-8869(02)00005-3

Wagner, R. K. (1997). Intelligence, training, and employment. *American Psychologist, 52,* 1059–1069. doi:10.1037//0003-066X.52.10.1059

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive Test of Phonological Processing: CTOPP examiner's manual*. Austin, TX: Pro-Ed.

Warren, D. H. (1994). *Blindness and children: An individual differences approach.* Cambridge, UK: Cambridge University Press.

Wechsler, D. (2003). *WISC-IV technical and interpretive manual.* San Antonio, TX: Psychological Corporation.

Wilton, A. (2011). Implications of parent–child interaction for early language development of young children with visual impairments. *Insight: Research and Practice in Visual Impairment and Blindness, 4,* 139–147.

Woodcock, R. W. (1993). An information processing view of Gf-Gc theory. *Journal of Psychoeducational Assessment*, *8*, 231–258.

Table 1

Participant Demographics

Sex	Age	Visual Condition	Visual Abilities	Age of Onset of Visual Condition (in years)
F	16	Retinopathy of prematurity	Light perception	4
M	20	Glaucoma	Some form perception	12
F	21	Anophthalmia	None	0
M	16	Retinal detachment	None	<1
M	13	Unknown	None	2
M	15	Glaucoma and Aniridia	Some form perception	0
M	18	Retinal detachment	None	5
F	14	Unknown	None	4
F	15	Leber's Optic Neuropathy	Some form perception	0
M	16	Medulablastoma	None	8
F	14	Bilateral Micropthalmia	None	0
F	13	Retinal detachment	Some form perception	0
M	18	Bilateral Anophthalmia	None	0
M	16	Norrie Disease	None	0
F	15	Leber's Congenital Amorosis	Some form perception	0
F	14	Optic Nerve Hypoplasia	Some form perception	0
M	17	Retinopathy of prematurity	None	0
M	13	Familial Exudative Vitreoretinopathy	Light perception	0
F	15	Retinopathy of prematurity	Light perception	0

Note: "Light perception" indicates that the participant can determine whether a room is light or dark. "Some form perception" indicates that the participant can see large forms (e.g., a building in close proximity or a human figure moving toward them).

Table 2

Internal Consistency of Measures for the Current Sample

Instrument	α
CTOPP Rapid Automatic Naming	.987
WASI Vocabulary	.754
KeyMath-R Addition	.809
KeyMath-R Multiplication	.762
KeyMath-R Mental Computation	.919
KeyMath-R Problem Solving	.907
DIBELS Oral Reading Fluency	.985
BLAT	.902

Table 3

Correlation Coefficients for Convergent and Discriminant Validity Analyses – Full Sample

Instrument	Correlation with TPSF	Correlation with tactile processing speed accuracy
CTOPP Rapid Naming: Letters	-.53	-.56
CTOPP Rapid Naming: Numbers	-.41	.07
WASI Vocabulary	.58	.54
KeyMath-R Addition	.71	.76
KeyMath-R Multiplication	.63	.76
KeyMath-R Mental Computation	.68	.47
KeyMath-R Problem Solving	.71	.59
DIBELS Oral Reading Fluency	.40	.37
BLAT	.73	.65

Table 4

Correlation Coefficients for Convergent and Discriminant Validity Analyses – CA Sample

Instrument	Correlation with TPSF	Correlation with tactile processing speed accuracy
CTOPP Rapid Naming: Letters	-.57	-.32
CTOPP Rapid Naming: Numbers	-.52	-.02
WASI Vocabulary	.57	.35
KeyMath-R Addition	.69	.75
KeyMath-R Multiplication	.60	.61
KeyMath-R Mental Computation	.81	.34
KeyMath-R Problem Solving	.65	.26
DIBELS Oral Reading Fluency	.71	.51
BLAT	.64	.62

Table 5

Correlation Coefficients for Convergent and Discriminant Validity Analyses – BC Sample

Instrument	Correlation with TPSF	Correlation with tactile processing speed accuracy
CTOPP Rapid Naming: Letters	-.59	-.82
CTOPP Rapid Naming: Numbers	.38	.24
WASI Vocabulary	.68	.63
KeyMath-R Addition	.90	.78
KeyMath-R Multiplication	.85	.85
KeyMath-R Mental Computation	.76	.54
KeyMath-R Problem Solving	.85	.73
DIBELS Oral Reading Fluency	.48	.62
BLAT	.73	.65

Figure 1. Cattell-Horn-Carroll (CHC) theory of intelligence. This figure illustrates McGrew's combination of Cattell and Horn and Carroll's theories of intelligence, including the most up-to-date structure summarized in Schneider and McGrew (2012).

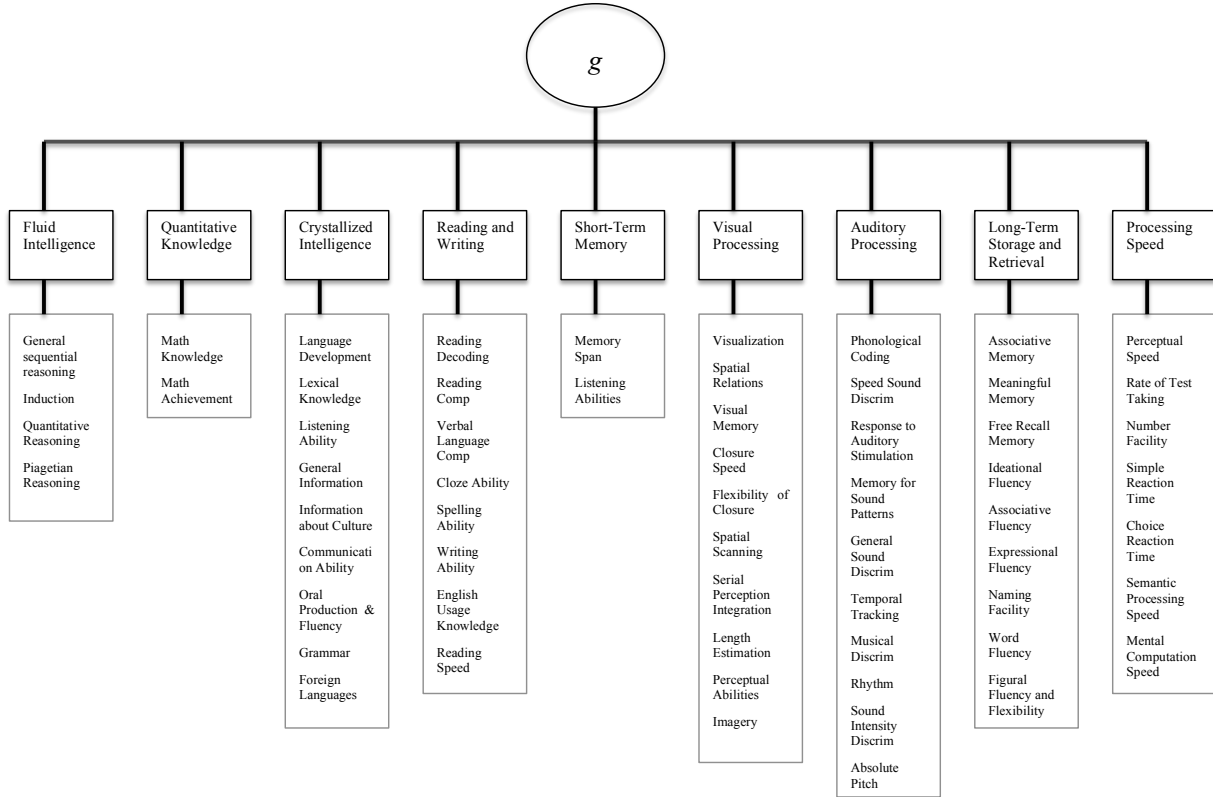| g								
Fluid Intelligence	Quantitative Knowledge	Crystallized Intelligence	Reading and Writing	Short-Term Memory	Visual Processing	Auditory Processing	Long-Term Storage and Retrieval	Processing Speed
General sequential reasoning	Math Knowledge	Language Development	Reading Decoding	Memory Span	Visualization	Phonological Coding	Associative Memory	Perceptual Speed
Induction	Math Achievement	Lexical Knowledge	Reading Comp	Listening Abilities	Spatial Relations	Speed Sound Discrim	Meaningful Memory	Rate of Test Taking
Quantitative Reasoning		Listening Ability	Verbal Language Comp		Visual Memory	Response to Auditory Stimulation	Free Recall Memory	Number Facility
Piagetian Reasoning		General Information	Cloze Ability		Closure Speed	Memory for Sound Patterns	Ideational Fluency	Simple Reaction Time
		Information about Culture	Spelling Ability		Flexibility of Closure	General Sound Discrim	Associative Fluency	Choice Reaction Time
		Communication Ability	Writing Ability		Spatial Scanning	Temporal Tracking	Expressional Fluency	Semantic Processing Speed
		Oral Production & Fluency	English Usage Knowledge		Serial Perception Integration	Musical Discrim	Naming Facility	Mental Computation Speed
		Grammar	Reading Speed		Length Estimation	Rhythm	Word Fluency	
		Foreign Languages			Perceptual Abilities	Sound Intensity Discrim	Figural Fluency and Flexibility	
					Imagery	Absolute Pitch		

Figure 2. Tactile symbols used on the adapted tactile processing speed measure. This figure depicts the five tactile symbols (presented here as black and white line drawings) selected from the studies on tactile cartography to be included in the adapted tactile processing speed measure.

1	2	3	4	5	6	7	8	9
^	u	+	¢	¤	✔	Π	Ξ	□

SAMPLE ITEMS

2	1	4	6	3	5	2

TEST ITEMS

1	2	5	1	3	1	5	4	2	7

5	6	9	2	5	8	4	6	1	8

7	5	4	8	6	9	4	3	1	8

2	9	7	6	2	5	8	7	3	6

4	5	9	1	6	8	9	3	7	5

1	4	9	1	5	8	7	6	9	7

8	2	4	8	3	5	6	7	1	9

Figure 3. Mock-up of WISC-IV Coding subtest. This is a sample of a task similar to the WISC-IV Coding subtest. Due to copyright, the original task cannot be presented here. The student is required to draw the appropriate symbol, one by one. The maximum time allotted is two minutes.
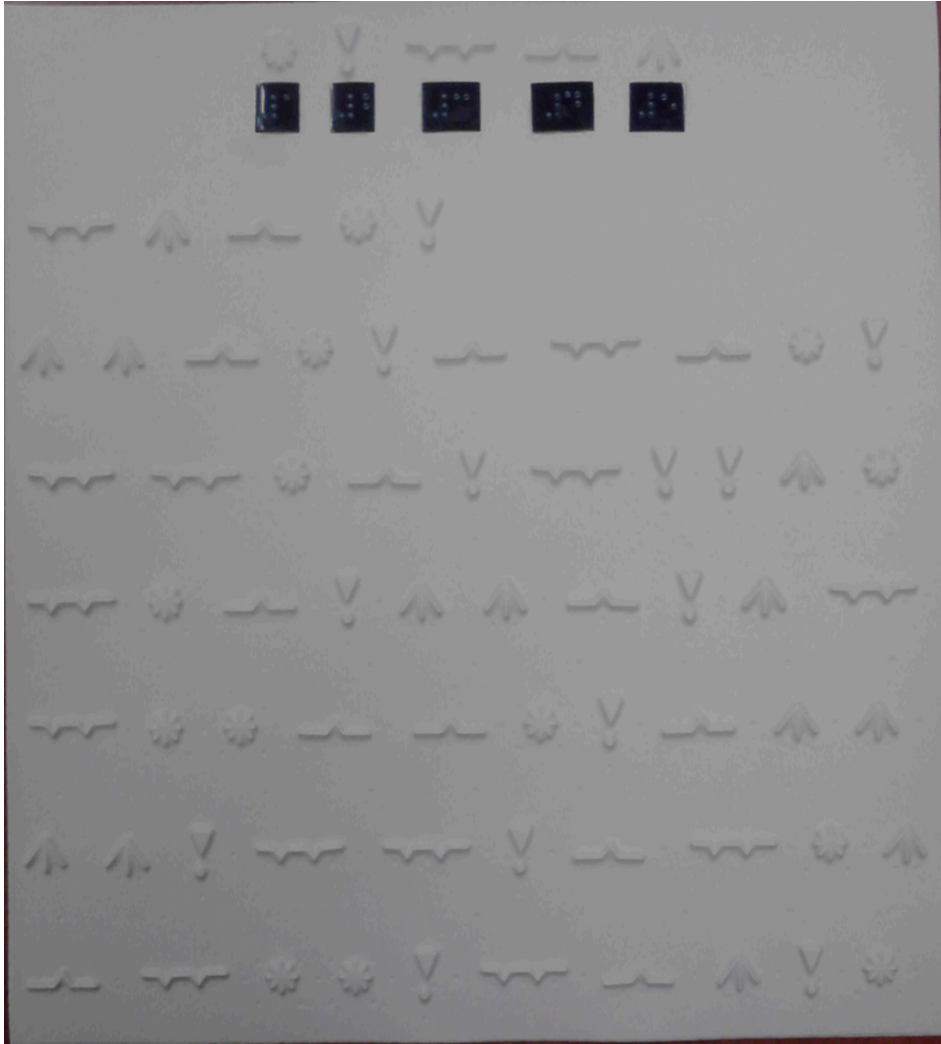
Figure 4. Photograph of adapted tactile processing speed measure. This is a photograph of the actual adapted tactile processing speed measure. The symbols in the top row are paired with a braille number below (the black squares contain the braille numbers). The first left-aligned row with five items is the sample row. The remaining six rows are the actual scored and timed test items.
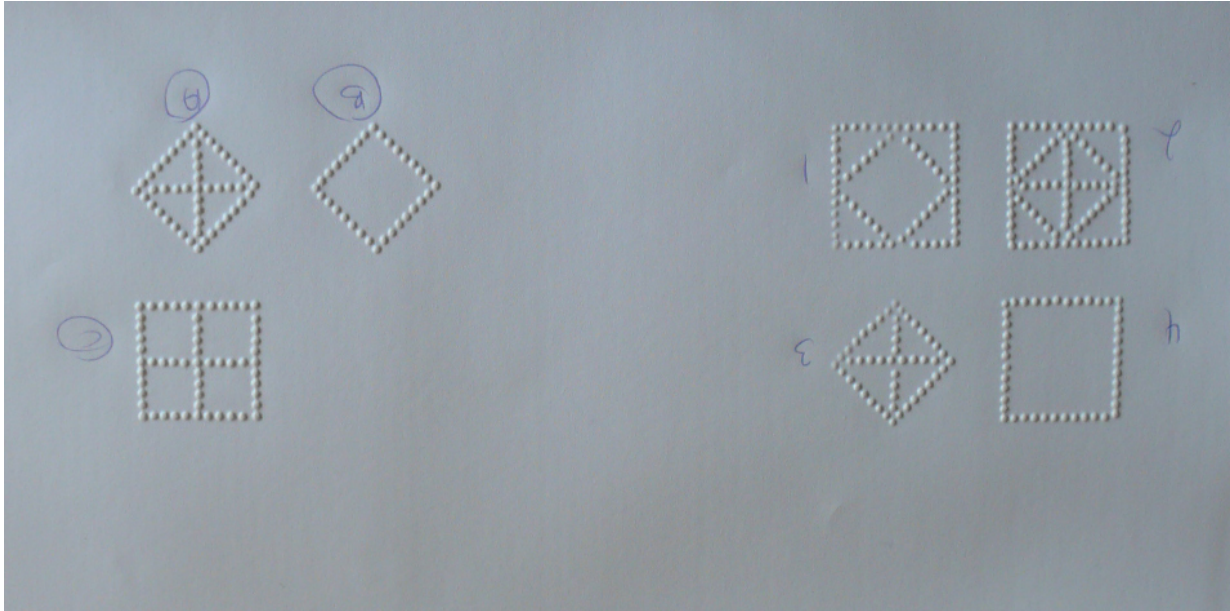
Figure 5. Photograph of sample Blind Learning Aptitude Test (BLAT) item. This photograph depicts a sample matrix reasoning item from the BLAT. The cluster of three items on the left is the matrix reasoning problem, with one "missing" item. The four options on the right represent the four stimuli from which the participant can select.