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The Comprehension of STEM Graphics via a Multisensory Tablet Electronic Device by Students with Visual Impairments

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Abstract

Introduction: The current work probes the effectiveness of multimodal touch screen tablet electronic devices in conveying science, technology, engineering, and mathematics graphics via vibrations and sounds to individuals who are visually impaired (i.e., blind or low vision) and compares it with similar graphics presented in an embossed format. **Method:** A volunteer sample of 22 participants who are visually impaired, selected from a summer camp and local schools for blind students, were recruited for the current study. Participants were first briefly ($\sim$30 min) trained on how to explore graphics via a multimodal touch screen tablet. They then explored six graphic types (number line, table, pie chart, bar chart, line graph, and map) displayed via embossed paper and tablet. Participants answered three content questions per graphic type following exploration. **Results:** Participants were only 6% more accurate when answering questions regarding an embossed graphic as opposed to a tablet graphic. A paired-samples *t* test indicated that this difference was not significant, $t(14) = 1.91$, $p = .07$. Follow-up analyses indicated that presentation medium did not interact with graphic type, $F(5, 50) = 0.43$, $p = .83$, nor visual ability, $F(1, 13) = 0.00$, $p = .96$. **Discussion:** The findings demonstrate that multimodal touch screen tablets may be comparable to embossed graphics in conveying iconographic science and mathematics content to individuals with visual impairments, regardless of the severity of impairment. The relative equivalence in response accuracy between mediums was unexpected, given that most students who participated were braille readers and had experience reading embossed graphics, whereas they were introduced to the tablet the day of testing. **Implications for practitioners:** This work illustrates that multimodal touch screen tablets may be an effective option for general education

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teachers or teachers of students with visual impairments to use in their educational practices. Currently, preparation of accessible graphics is time consuming and requires significant preparation, but such tablets provide solutions for offering "real-time" displays of these graphics for presentation in class.

Keywords

accessible graphics, multimodal feedback, tactile feedback, vibrations, touchscreens, STEM education

A persistent, though improving, challenge for classroom instructors is the creation of accessible course content for students with visual impairments (i.e., those who are blind or have low vision; Zhou, Parker, Smith, & Griffin-Shirley, 2011). Although assistive technology such as video magnifiers, braille embossers, and note-taking devices aid in making content accessible, several studies have found that many students with visual impairments in the United States do not use assistive technology in the classroom despite its clear benefit to learning. Albeit, its prevalence is increasing (Kelly, 2009). Unfortunately, the use of assistive technology in classrooms often requires extensive instructor training, can be difficult to teach to students, and can be expensive, particularly for schools in nonindustrialized nations (Pal, Pradhan, Shah, & Babu, 2011; Zhou et al., 2011). Thus, barriers peripheral to intellect, willingness to learn, and commitment to schoolwork can prevent the maximization of a child's scholastic potential.

Commonplace technology, such as multimodal touch screen electronic devices, provides a promising new platform with the potential to serve as a consumer technology capable of improving graphical access for students with visual impairments. Touch screen platforms, including Android and iOS, provide visual, tactile (vibratory), and auditory feedback, enabling the colocation of visual information with nonvisual feedback cues. Given that similar information conveyed through multiple sensory inputs can result in increased perceptual detail (Macaluso & Maravita, 2010), such platforms are poised to serve as a medium to convey visual information via nonvisual feedback modalities.

The study of multimodal touch screen devices as educational tools is still in its infancy. The advantages of such technology include their (1) portability and capability to perform multiple tasks at once; (2) ability to provide simultaneous visual, auditory, and tactile feedback; (3) adoption within educational settings; (4) low cost, (5) ubiquitous use; and (6) wide adoption compared to task-specific devices, meaning there is no apparent stigma associated with its use. Several studies have illustrated the potential of this technology in conveying simple graphical concepts via multisensory inputs for students with visual impairments (e.g., Giudice, Palani, Brenner, & Kramer, 2012; Goncu & Marriott, 2011; Gorlewicz, Burgner, Withrow, & Webster, 2014; Tennison & Gorlewicz, 2016).

As reviewed by O'Modhrain, Giudice, Gardner, and Legge (2015), however, challenges still exist in the development of touch

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screen devices intended to improve graphical access for individuals with visual impairments. First, constraints of tactile perception pose a significant barrier to the creation of accessible educational content (Loomis, Klatzky, & Guidice, 2012). Namely, tactile exploration is focal and limited in spatial resolution and bandwidth. The conversion of visual to tactile graphics is not always straightforward, given the diversity of perceptual subsystems. Second, most touch screens require a single point of contact during exploration (i.e., a single finger pad). This design is troublesome, given that some skilled braille readers tend to use both hands and multiple fingers to understand spatial orientation (Craig, 1985; Mousty, 1986; Ulusoy, 2015; Wong, Gnanakumaran, & Goldreich, 2011).

Third, O'Modhrain and colleagues (2015) argued that line tracing can be difficult for individuals with visual impairments because a touch screen surface is flat and nontextured. However, in recent, unpublished, studies, our group has found that children with visual impairments closely traced uniform and nonuniform line orientations (~8.9 mm thick) on a tablet. Line boundaries were denoted by distinctive tactile (vibratory) or auditory cues. Results indicated that participants' average line deviations ranged from 13.11 to 16.51 mm, which is smaller than the width of an average adult finger pad.

We acknowledge the limitations to multisensory touch screen devices in the presentation of visual information. However, in addition to the numerous advantages of touch screen devices already discussed, they are increasing in sophistication and capability while being adaptive and flexible to user demands. In addition, we agree with O'Modhrain and colleagues (2015), who argued that despite these limitations, multisensory touch screen devices have great potential in improving accessibility for individuals with visual impairments and should therefore continue to be explored as a universally designed platform.

Although multimodal touch screen tablets pass the face validity test as an efficacious educational resource, comparative testing to traditional assistive technology is lacking. Giudice, Palani, Brenner, and Kramer (2012) asked sighted (blindfolded) participants and participants with visual impairments to explore and answer questions regarding graphics (letters, shapes, and bar charts) presented via a multimodal touch screen tablet. Performance was then compared to an embossed graphic condition. Three successive experiments indicated that all participants were as accurate in their responses following the exploration of graphics presented via a multimodal touch screen as they were to those that were embossed. Similar findings regarding the educational utility of multimodal touch screen devices have been reported elsewhere (see Brock, Truillet, Oriola, Picard, & Jouffraise, 2015; Raja, 2011). These reviewed studies, however, are limited in methodology, sample size, sample characteristics (i.e., the reliance on blindfolded participants), and scope, demonstrating a clear need for further research.

Although the exploration of simple graphics via a multisensory touch screen device has been the focus of earlier studies, it remains unclear whether advanced science, technology, engineering, and mathematics (STEM)-based graphics (i.e., those that are more technical than fundamental geometries like shapes, points, or grids) can be explored to the same degree of precision. Similarly, little evidence exists on whether multimodal touch screens are as effective as traditional assistive technology in communicating graphical content. In this work, we bridge this gap and present a comparative study that explores how accurate individuals are at extracting information from core graphical concepts displayed via embossed graphics and multisensory consumer touch screen devices. On a Samsung Galaxy Tab S tablet device, we installed the ViTAL (2018) software application, a classroom tool capable of presenting multisensory content in real time. Common STEM graphical concepts were displayed on the Tab S with ViTAL software and in an embossed form to children with visual impairments. As will be discussed in the Method section, participants were trained how to explore these graphics using the tablet. The experimental trials required participants to explore and answer questions regarding several graphics presented in embossed and electronic mediums. In addition, participants completed a questionnaire regarding their educational and health histories, and they provided subjective feedback regarding the testing session, the Tab S device, and the ViTAL application.

Method

Participants

Students with visual impairments ($N = 22$, 11 female/11 male, $M_{age} = 15.45$, age range $= 10–22$ years) were recruited from four sites including a summer camp at which independent living skills are taught and three Midwestern schools for blind students. These sites tend to recruit students with visual impairments from diverse educational backgrounds (i.e., students in general education and special education settings), although we did not directly assess educational histories. We acknowledge that varying school settings of our participants likely affected the accessibility issues they may have experienced, which should be considered in interpreting the results of our study. A researcher was present on-site to overview study objectives, attain consent from participants (or guardians, for minor participants), and review Health Insurance Portability and Accountability Act (HIPAA) protections. Children below the age of 13 years and individuals with typical vision were excluded from the study. This age restriction was added midway through data collection because several younger participants failed to understand certain mathematical concepts. Participants were compensated with a gift card. The study protocol was approved by the Saint Louis University Institutional Review Board.

Materials

Demographics questionnaire

Participants were first administered a self-report demographics questionnaire upon arrival to the testing room. Age, sex, grade level, handedness, presence of additional disabilities, number of years since diagnosis of visual impairment, severity of visual impairment, primary learning channel, and preferred operating system were collected.

Samsung Galaxy Tab S and ViTAL application

A 10.5″ Samsung Galaxy Tab S was used to display multisensory graphical content. Six bump dots and four rubber bands were placed along the perimeter of the tablet screen to serve as a preliminary form of ensuring the participants are easily able to stay within the active screen area, which prior work illustrated was difficult without physical boundaries (see Figure 1).

Installed on the Tab S was the ViTAL application. Eighteen graphics (Training [6], "Question Set #1" [6], and "Question Set #2" [6]) were uploaded to the application. Exemplary graphics annotated with feedback are shown in Figure 2. Once the participant number and session code were entered, the first training graphic appeared. The following graphics were displayed during training and testing phases: number line, table, pie chart, bar chart, line graph, and map. These

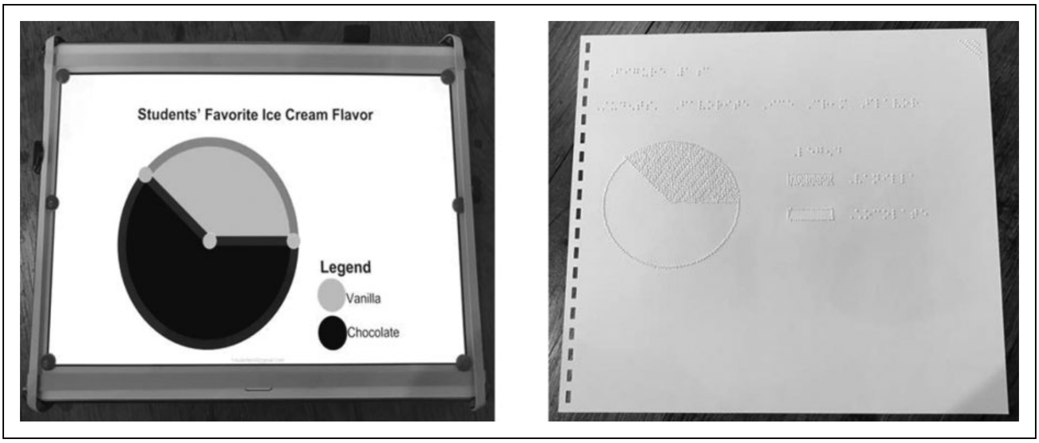

Figure 1. Samsung Galaxy Tab S/ViTAL application and embossed example graphic.

graphics were chosen because they represent some of the core graphical concepts found in mathematics and science curriculums at the middle and high school levels.

Each touch screen graphic provided auditory and vibratory feedback when the participant ran his or her finger across components of the image. All text within the image was read aloud via text to speech. For instance, the maps used in this study contained "vibratory tags" that vibrated when a street or landmark was touched and "auditory tags" that read aloud street names or landmarks when they were touched. Throughout the study, the researcher (Hahn) swiped the tablet to advance participants to the next image.

Embossed graphics

All graphics developed for the ViTAL application (excluding training graphics) were created using a braille embosser by an orientation and mobility specialist–teacher of students who are visually impaired (Hollinger) employed by a local school district (see Figure 1).] This educator has worked with individuals with visual impairments for approximately 20 years, is fluent in tactile graphic software, and is well versed in tactile graphics and access technology. The 12 graphics were embossed on 12″ × 11″ single sheets of paper. Maps required an additional sheet of paper to accommodate legends. The educator generated these graphics to be quality tactile graphics that would be created for a student learning these concepts.

Content assessment form

Three questions were developed for each graphic to assess participant comprehension following exploration. Questions were adapted from standard educational materials (e.g., textbooks) received from a local residential school for visually impaired students. We worked with the educator to model our study questions from these standardized materials, carefully choosing content that was at the appropriate grade level for participants. In addition, our assessment form was cross-validated by an expert consultant independent of our research team. The consultant has extensive experience with students with disabilities (including those with visual impairments) and is an expert in technology-based instruction, universal design, and development of assessment and evaluation instruments in these contexts.

Exit questionnaire

Participants were asked questions regarding their educational histories and perceptions of

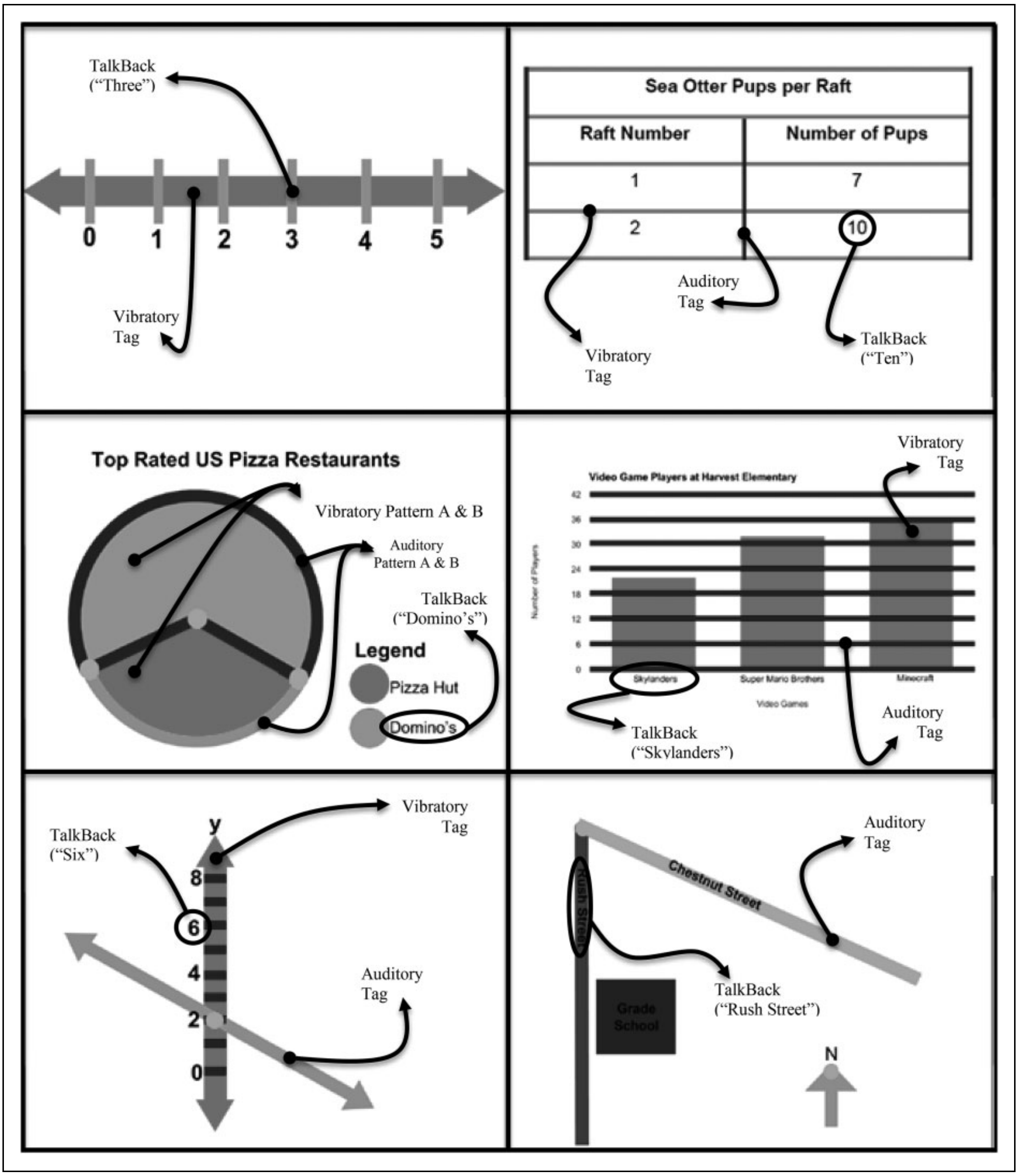

Figure 2. ViTAL training graphics annotated with in-text callouts for description of feedback provided.

the touch screen application. This questionnaire was intended to gain feedback on the display of graphics via the touch screen technology. In addition, the exit questionnaire enabled us to better understand how much of a problem content inaccessibility was for our participants.

The frequency of problem inaccessibility and content delay in the classroom was assessed via a 1–6 scale (1 = *never*, 6 = *daily*). In addition, the degree to which these issues were viewed as obstructive to their educational experience was measured on a 1–5 scale (1 = *not a problem*, 5 = *very big* *problem*). Participants were also asked whether it was easier to explore graphics via embossed paper or tablet, whether the tablet could replace any existing technology that they use, and the strengths and weaknesses of the touch screen application. Finally, motivation was assessed for some, but not all, participants because the researcher observed that several participants were not providing maximal effort early in the data collection process. Motivation was assessed using a 1–5 scale (1 = *not very motivated*, 5 = *very motivated*).

Procedure

Participants were greeted by the researcher upon arrival, and information outlined in the consent and HIPAA forms were reviewed. Participants were then asked to complete the demographics questionnaire. The researcher read aloud each question and corresponding answer choices to participants.

Instructions were then provided to participants for the comparative testing. They were told that they would be given 12 mathematics or science graphics (6 by tablet and 6 on embossed paper) and would be asked questions about them. They were advised that they could take as much time as needed and asked to respond "I do not know" if they did not know an answer. Participants were given the opportunity to ask questions before training commenced. Condition order was fully counterbalanced.

Half of the participants then proceeded to be trained on the tablet and ViTAL application. Training always preceded the tablet experimental trials. Participants first explored the tablet with the screen turned off to adjust to the active screen area. Participants were then provided instructions and strategies to explore each graphic. Specifically, they were instructed to use a single finger, to slowly glide their finger across the tablet screen, and to utilize the bump dots and rubber bands as "points of reference." Moreover, participants were encouraged to select a specific bump dot as a starting point that they could return to if they became disoriented during exploration and to place their thumb at the bottom of the tablet to serve as another point of reference, a tactic users in our previous work found useful.

The researcher then turned on the tablet screen to display the training graphics within the ViTAL application. During graphic exploration, the vibratory and audio features of each graphic were explained, and two or three guiding questions per graphic were provided to facilitate learning (e.g., "How many rows are there in the table?" "What is the highest y-axis value in the bar chart?"). Participants received additional support as needed (e.g., researcher guided participant's hand) and were given an indefinite amount of time to progress through all graphics. Training graphics were presented in a partially counterbalanced order, and the training period lasted less than 30 min.

After training, the experimental trials for the tablet condition commenced. Participants were asked three questions per graphic in a fixed, sequential order. Again, participants were presented with the same type of graphic as was presented in the training session but not the exact same graphic. For those with usable vision, their sight was not occluded during the task because (1) we sought to understand the utility of each medium in conveying iconographic information across the visual acuity spectrum and (2) we could perform exploratory analyses investigating whether there was an interaction between presence of a sightedness and medium on task performance. Graphic presentation order was the same as training to (1) maintain consistency and (2) control for order effects. Although the participants were not timed, they were encouraged to produce an answer if an excessive amount of time had elapsed (>5 min/problem). Researcher feedback was minimal: Positive or negative feedback following responses was never provided, but encouragement was given if participants showed signs of frustration or disinterest. In addition, breaks were provided when needed or requested.

Like the tablet condition, participants were also asked to explore and answer questions regarding six embossed graphics. Participants were not trained on how to interpret the embossed graphics, since they were all either currently learning or familiar with embossed graphics. Graphics were presented sequentially and in an identical order to the tablet condition, and a similar protocol as the tablet condition was followed in this condition.

To ensure performance was not material-specific, two variants were created for each graphic type: Two alternate question sets were constructed that differed in one or two key features (e.g., the number 7 is circled on "Number Line #1," whereas 5 is circled on "Number Line #2"). These differences were introduced to (a) ensure that problem difficulty was comparable across conditions and (b) reduce the likelihood of a potential interaction between condition and problem. Therefore, half of the participants were assigned one condition-and-material pairing and the remaining half the opposite pairing.

The study concluded after the researcher administered the exit questionnaire. The exit questionnaire was given last to prevent biasing participant performance or allowing participants to become privy to our research hypotheses. Participants were encouraged to provide their honest opinions regarding the technology and were reminded that the researcher had no vested interest in the outcome of the study. Study sessions typically lasted approximately 60 min.

Results

Power analysis

A post hoc power analysis using G*Power 3.1 statistical software determined that an appropriate sample size of $N = 15$ would be required ($1 - \text{beta} > .80$, Cohen's $d = .8$) for our specific hypotheses.

Descriptive statistics

Twenty-two participants were enrolled in the current study. However, five participants were not included in subsequent analyses because of motivation issues (3), language barriers (1), and level of braille literacy (1). Second, not every participant viewed every graphic, since some were unfamiliar with certain concepts (e.g., line graphs). Third, small changes were made for some graphics midway throughout testing (e.g., thicker lines, more distinct vibratory patterns, and the like). Thus, we use "Study 1" to refer to testing prior to these changes ($n = 9$), and "Study 2" to testing following these changes ($n = 8$), though we acknowledge that performance was not statistically different between these two groups, enabling them to be combined in our subsequent analyses as detailed below.

The breakdown of age, sex, grade, and vision level of the analytic sample is reported in Table 1. The sample was heterogeneous in terms of age, grade level, and visual acuity. This latter point is noteworthy given that differences in visual acuity might underlie differences in performance (see Exploratory analyses section). The percentage of correct responses is reported in Table 2. Participants were slightly more accurate (+6%) in their responses in the embossed condition, although this difference was not statistically significant, see "Analysis of variance (ANOVA)" section. Feedback regarding the technology is listed in Table 3. Descriptive statistics for several exit questionnaire items are reported in Table 4. Most participants reported that their teachers were unable to convert a graphic into an

Table 1. Participant demographics.

M_{age} (SD)	Study 1 ($n = 9$) 15.22 (3.77)	Study 2 ($n = 8$) 16.75 (2.25)	Combined ($N = 17$) 15.94 (3.15)
Sex			
Male	3	6	9
Female	6	2	8
Grade			
Fifth grade	1		1
Sixth grade	1	1	2
Eighth grade	1		1
Ninth grade	2	1	3
Tenth grade	1		1
Eleventh grade		2	2
Twelfth grade	3		3
Graduated higher secondary		4	4
Vision impairment severity[a]			
Moderate		2	2
Severe	3	5	8
Complete	6	1	7
Additional disabilities[b]			
Attention deficit hyperactivity disorder		1	1
Cerebral palsy		1	1
Speech–language impairment		1	1
Primary learning channel[b]			
Visual		4	4
Tactile	7	3	10
Auditory	7	5	12
Preferred operating system[b]			
Android	2	4	6
iOS	8	6	14
Windows	3	4	7

[a]Moderate impairment = use of prescription lenses to view materials; severe impairment = preserved light or object perception or both; complete impairment = cannot see light.
[b]Participants could report multiple response options for these questions.

accessible format at least once within the past month (12) and that there was a delay in the provision of accessible content at least once within the past 6 months (11).

Analysis of variance (ANOVA)

Confirmatory analyses

Condition order, condition-and-material pairing, and graphic order were all counterbalanced to reduce the likelihood of systematic bias. To test whether performance varied as a function of these factors, several ANOVAs were conducted. In all such cases, group differences were not significant. Similarly, an ANOVA was performed to determine whether participants enrolled in Studies 1 and 2 significantly differed in performance. Group differences were not apparent. This finding allowed for us to collapse across groups and studies to

Table 2. Percentage of correct responses.

Concept	Embossed graphics			Tablet graphics			Total
	Study 1 ($n = 9$)	Study 2 ($n = 8$)	Combined ($N = 17$)	Study 1 ($n = 9$)	Study 2 ($n = 8$)	Combined ($N = 17$)	
Number line	92 (8)	90 (7)	91 (15)	81 (9)	92 (8)	86 (17)	89
Table	100 (8)	90 (7)	96 (15)	96 (9)	92 (8)	94 (17)	95
Pie chart	93 (4)	94 (6)	94 (10)	78 (6)	100 (7)	90 (13)	92
Bar chart	92 (8)	83 (6)	88 (14)	67 (9)	86 (7)	75 (16)	81
Line graph	81 (6)	83 (6)	82 (12)	67 (8)	81 (7)	73 (15)	77
Map	58 (8)	86 (7)	71 (15)	70 (9)	71 (8)	71 (17)	71
Total	86	88	87	77	87	81	84

Note. Some participants did not explore all embossed or tablet graphics. The number of participants exploring each graphic type is reported in parentheses beside the percentage of correct responses.

increase the statistical power of subsequent analyses.

A paired-samples t test was conducted on the proportion of correct responses, with medium as the within-subjects factor. A comparison of means indicated that there was no significant difference in performance between embossed and tablet graphics, $t(14) = 1.91$, $p = .07$.

Exploratory analyses

An exploratory 2 (embossed, tablet) $\times$ 6 (number line, table, pie chart, bar chart, line graph, map) factorial ANOVA was conducted on the proportion of correct responses to determine whether participant performance on individual graphic types varied across mediums. There were no main effects of medium, $F(1,10) = 1.16$, $p = .31$, nor graphic, $F(5, 50) = 1.64$, $p = .17$, and there was no interaction between condition and graphic, $F(5, 50) = 0.43$, $p = .83$.

One final exploratory analysis was performed to address whether level of visual impairment influenced performance within or across mediums. For this analysis, participants with moderate (use of prescription lenses to view materials; $n = 8$) or severe (light or object perception or both; $n = 2$) visual impairment were classified into a single group (low vision) and then compared to those with complete blindness ($n = 7$). There were no main effects of condition, $F(1, 13) = 0.44$, $p = .52$, nor sightedness, $F(1, 13) = 2.37$, $p = .15$, and there was no interaction, $F(1, 13) = 0.00$, $p = .96$.

Discussion

Although extant literature suggests that multimodal, consumer touch screens could convey iconographic information as well as traditional embossed materials, few studies have directly investigated this question. Our results suggest that participants did not significantly differ in response accuracy following the exploration of tactile graphics via electronic and traditional mediums. Follow-up exploratory analyses further indicated that similar performance across mediums was evident regardless of problem type and level of visual impairment.

These findings are notable for several reasons. First, most participants had extensive experience in reading braille, whereas they were introduced to the tablet and application over a brief training period. Although

Table 3. Samsung Galaxy Tab S and ViTAL feedback.

Positive feedback	Negative feedback
"Haptic and auditory feedback helpful in understanding orientation and graphic information" (9)	"Graphic lines should be thicker" (4)
"Sounds and/or vibrations [are] engaging" (7)	"Easier to make simple errors" (2)
"Resourceful with space" (2)	"[Does not provide] enough haptic/auditory feedback" (1)
"Keys/legends [are] easier to read" (1)	"Only one finger can touch screen" (1)
"Easier to explore graphic boundaries" (1)	"Audio sounds [are] repetitive" (1)
"Portable" (1)	"Vibrations [are] too soft" (1)
	"Hard to find intersections" (1)
	"Empty space [is] confusing" (1)

exploration strategies were provided, we did not expect this training to negate the learning curve of a new technology, and indeed, some participants struggled. Nevertheless, the relative equivalence in performance is promising given the unfamiliarity of this new medium. In addition, our study utilized a diverse array of STEM graphics, illustrating the feasibility of displaying both basic and more complex concepts by way of a multimodal tablet.

When considering that using the Tab S running ViTAL software is more cost-effective than most assistive technology devices and that the hardware is a readily available consumer product, its potential importance becomes apparent. Of those analyzed, 12 participants reported that their teachers were unable to convert a graphic into an accessible format at least once within the past month, and 11 claimed that there was a delay in content creation at least once within the past 6 months. These issues can impede a student's academic progress, thus making solutions such as multimodal touch screens critical to bridging the accessibility gap, particularly as educational content continues to move to electronic forms.

Another advantage that ViTAL has over traditional assistive technology is that it can be refined and improved upon user feedback (see Table 3). For instance, concerns of "boundary line thickness," "the efficient use of space," and "the use of repetitive audio sounds" can easily be addressed. Other negative comments, including that it is "easier to make simple errors" and "only one finger can touch the screen," are concerning, but

Table 4. Samsung Galaxy Tab S and ViTAL exit questionnaire frequencies.

Question	*n*	%
How often are you unable to participate in class due to a delay in content?		
Everyday	3	17.6
Every week	1	5.9
Every month	3	17.6
Every 6 months	4	23.5
Every year	1	5.9
Never	5	29.4
How often does a teacher present an inaccessible problem during class?		
Everyday	5	29.4
Every week	4	23.5
Every month	3	17.6
Every 6 months	1	5.9
Every year	2	11.8
Never	2	11.8
ViTAL's software is easier than embossed graphics to use.		
Strongly disagree	4	26.7
Disagree	1	6.7
Undecided	3	20.0
Agree	4	26.7
Strongly agree	3	20.0

these aspects did not appear to significantly affect performance. We believe that with experience and practice, effective and individualized search strategies can be developed, making the tool easier to use over time. Conversely, several positive comments were also voiced by participants (e.g., “sounds and vibrations are engaging” and “graphic orientation [is] easy to understand”), and perhaps most importantly, nearly half of respondents reported to prefer the tablet, even though the study represented their first exposure to it.

Limitations

Our study was limited in that our sample was diverse in several respects. Visual acuity and the number of years since diagnosis differed across participants—an important consideration given that congenitally blind and adventitiously blind individuals differ in tactile acuity, functional independence, and neural networking (Pawluk, Adams, & Kitada, 2015; Wong et al., 2011). However, an exploratory analysis indicated that participants who are totally blind compared to those with low vision did not significantly differ in performance. Participants also varied in age, grade level, and presence of additional disabilities. Although these factors are all notable, variance within the population who are visually impaired is common. Further, this variance is not necessarily seen as a negative aspect of this study since it represents a realistic use case.

Second, although our sample size is high compared to other technology-related user studies of this population, the null results observed might reflect inadequate statistical power. Although our power analysis indicated that we could likely detect the presence of a statistically significant difference between conditions given our sample size, a larger sample is still desired. Third, questions were administered verbally (for ease of access). We note that this condition inherently tests not only participant’s conceptual knowledge but also their listening comprehension; however, this mode of questioning was consistent across both the tablet and the embossed conditions. To minimize the load on verbal working memory, questions were repeated when participants requested. Fourth, exploration time was not measured. We would expect that participants would demonstrate a quicker solution in the embossed condition given their familiarity with the medium, although this cannot be confirmed from this study. We note, however, that the study was limited in time and both conditions received approximately equal time allocations. No noticeable difference was observed by the experimenter. It would be interesting to compare time in future work to understand not just learning comprehension but also efficiency.

Finally, some students demonstrated motivational issues during testing and were excluded from the analytic sample. Although motivation was not objectively measured for many, signs of frustration (e.g., excessive sighing) and disinterest (e.g., unresponsiveness to prompts) were evident in some instances. It is worth noting that direct questions to assess motivation were not asked, since they could lead to the influence of response bias or the desire to be viewed favorably by the experimenter. Therefore, in all such instances, the researcher relied primarily on subjective observations of participant behavior and directed questions (e.g., “How are you feeling about the task thus far?”) to assess a participant’s level of engagement. In addition, measures such as taking breaks, engaging in casual conversation, and the like were taken to encourage task interest.

There was no discernable difference in motivation on the basis of age, sex, visual acuity, or order in which the conditions were completed. However, if participants demonstrated motivational issues, it was while exploring graphics via the tablet. We hypothesize that personality might influence motivation, and subsequently performance, in the tablet condition. In particular, individuals who tend to be less open or expressive might view new challenges such as learning to explore graphics via a multimodal touch screen tablet as unwelcome. Indeed, future research should investigate potential moderators of motivation and performance.

Perhaps the greatest strength of our study was its breadth and depth in methodological design. We employed a within-subjects design, allowing for a direct comparison of performance across mediums, and several potential confounds were controlled for through counterbalancing. Encouragingly, both objective and subjective measures indicated that the ViTAL application was comparable to embossed graphics. This finding is exciting, since it foreshadows a future where everyday consumer devices may become universal tools for all students regardless of ability and address many of their concerns and desires.

Implications for practitioners

This study sought to continue pushing the boundaries of our understanding of how touch screen devices—mainstream technology that is widely adopted in and out of schools and among individuals with visual impairments—can be leveraged as tools to access graphics. Our primary emphasis was toward understanding how a digital, multisensory, graphical representation could be interpreted compared with traditional embossed graphics. As educational content rapidly moves to the electronic space, we believe multisensory touch screens have the potential to serve as a platform for propelling these graphics beyond verbal descriptions, while also potentially alleviating the long lead time and specialized resources needed to create embossed tactile graphics. Equally important to the purpose of this study (understanding the potential affordances of touch screens for students) is understanding the potential utility of such devices for practitioners.

Working closely with an experienced teacher of students with visual impairments, the workflow of incorporating ViTAL software and a tablet in a classroom is designed as follows:

- The teacher, paraeducator, or materials staff member uses the ViTAL web portal, which is integrated with Google Classroom, to upload existing course content images.
- ViTAL's automated tools automatically recognize features and text in images (e.g., in a bar graph, the individual would need only click on one bar, and all subsequent bars of the same color are automatically recognized).
- Feedback in the form of vibrations and sounds are then selected for overlaying onto targeted features in the graphic.
- Gradients can also be applied so that sound or vibration intensities can change as an object is explored (e.g., as the bar goes higher, the pitch or vibration pattern intensity increases or both).

We note that the balance between automation and teacher markup in the tool is continuously evolving. Automation often decreases the time and effort required by the practitioner but also decreases the flexibility and personalization that can occur. ViTAL utilizes built-in optical character recognition to automatically recognize text in uploaded images, and this text is subsequently read aloud to the student when they move their finger over it. Additional custom auditory tags can also be added by the practitioner if desired. Once markup is complete, the multimodal images can be saved and immediately transferred into the student's content folder that can be accessed and explored via the tablet.

Future directions

Future studies will continue to investigate the limits of what is possible for multisensory graphic content, from both the student and practitioner perspectives. Future research should also continue to investigate how multimodal touch screens compare to other classroom aids (e.g., collage or swell graphics) in communicating fundamental STEM concepts. It is also important to understand the potential moderators of student performance (e.g., personality, cognitive ability, and the like) influencing successful exploration of iconographic content via new technology. Finally, the creation of these digital, multimodal images from the practitioner standpoint has yet to be explored. Such inquiries are necessary toward understanding how we can reduce the time required and the resources needed to bring accessible graphics into the hands of students.

Authors' Note

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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