University of Groningen

Tactile Working Memory Capacity of Users Who Are Blind in an Electronic Travel Aid Application with a Vibration Belt

van Erp, Jan ; Paul, Katja; Mioch, Tina

Published in:
ACM Transactions on Accessible Computing

DOI:
10.1145/3372273

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2020

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
van Erp, J., Paul, K., & Mioch, T. (2020). Tactile Working Memory Capacity of Users Who Are Blind in an Electronic Travel Aid Application with a Vibration Belt. *ACM Transactions on Accessible Computing*, *13*(2), [5]. https://doi.org/10.1145/3372273

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Tactile Working Memory Capacity of Users Who Are Blind in an Electronic Travel Aid Application with a Vibration Belt

JAN B. F. VAN ERP, TNO and University of Twente
KATJA I. PAUL, University of Groningen and Max-Planck Institute for Human Cognitive and Brain Sciences
TINA MIOCH, TNO

Electronic travel aids (ETAs) can increase the safety and comfort of pedestrians who have a visual impairment by displaying obstacles through a vibrotactile navigation belt. Building a complete picture of relevant obstacles and finding a safe route requires ETA users to integrate vibrotactile cues over time and space in their tactile working memory. Previous research suggests that the sense of touch exhibits a working memory that has characteristics similar to vision and audition. However, the capacity of the tactile working memory and the effects of secondary tasks are still under-researched. We investigated tactile working memory capacity of 14 adolescent participants who are blind in an immediate, whole report recall test. Participants received trials consisting of one to five vibration patterns presented sequentially at different locations on their torso representing obstacles with a direction (vibration location) and distance (vibration pattern). Recall performance was assessed under four conditions: baseline and with distracting background sounds and/or while walking with the long cane. Both walking and ignoring distracting sounds are relevant for everyday use of an ETA and were expected to decrease memory performance. We calculated the 75% correct scores for two memory performance measures: the number of items in a trial (numerosity), and item location and pattern correct. In the baseline condition, the scores were close to ceiling (i.e., 5 items). However, in the presence of distracting sounds and while walking, the scores were reduced to 3.2 items for numerosity and 1.6 items for location and identity correct. We recommend using 2 items as the maximum tactile working memory load in an applied setting unless users are trained and/or can adopt their strategy without unacceptable costs, such as reducing their walking speed.

CCS Concepts: • **Human-centered computing → User studies**; **Haptic devices**; **Accessibility technologies**;

Additional Key Words and Phrases: Tactile display, human information processing, working memory, electronic travel aids, blind

---

This research was supported by the EU FP7 SME Program, Project 605998 (Range-IT).

Authors' addresses: J. B. F. van Erp, Perceptual and Cognitive Systems, TNO, Soesterberg, The Netherlands, and Human Media Interaction, University of Twente, Enschede, the Netherlands; email: jan.vanerp@tno.nl; K. I. Paul, Institute of Artificial Intelligence and Cognitive Engineering, University of Groningen, Groningen, the Netherlands, and Max-Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany; email: k.i.paul@rug.nl; T. Mioch, Perceptual and Cognitive Systems, TNO, Soesterberg, the Netherlands; email: tina.mioch@tno.nl.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.
© 2020 Association for Computing Machinery.
1936-7228/2020/04-ART5 $15.00
https://doi.org/10.1145/3372273

ACM Reference format:
Jan B. F. van Erp, Katja I. Paul, and Tina Mioch. 2020. Tactile Working Memory Capacity of Users Who Are Blind in an Electronic Travel Aid Application with a Vibration Belt. *ACM Trans. Access. Comput.* 13, 2, Article 5 (April 2020), 14 pages.
https://doi.org/10.1145/3372273

---

1 INTRODUCTION

The somatosensory system is of increasing practical relevance as a solution to counteract the threat of visual and auditory overload in our information-rich environments or as one of the main channels of information presentation for users with impaired vision or audition. The World Health Organization [1] estimates that there are about 250 million people who have a moderate to severe visual impairment or who are blind. Orientation and mobility skills are essential for one's independence and can contribute to the quality of life. Therefore, the development of electronic travel aids (ETAs) adjusted to the requirements and preferences of pedestrians who are blind receives increasing attention [2, 3]. Here and in the remainder of this article, we use "users who are blind" for people with a visual impairment who can benefit from an ETA, including users who are legally blind and users with low vision. The aim of these ETAs is to assist users who are blind by partially restoring function with auditory or tactile input [4]. A good example is an obstacle detection system for pedestrians presenting the direction and distance of obstacles through vibration patterns on a tactile belt. Such vibration belts are based on solid perception research [5, 6] and have proven their value for simple navigation information like the directions of waypoints or obstacles under laboratory [7] and real-world circumstances [8]. However, building a coherent picture of the world necessitates the integration of sensory cues over time and space, and thus a mechanism for temporal storage of information. Although the perceptual aspects of vibrotactile navigation devices are well known, there is little research published on tactile working memory. Knowledge on the capacity of the tactile working memory, especially under conditions that simulate real-world usage, is indispensable to develop ETAs that are adjusted to the user's processing capabilities. We measured tactile working memory capacity of individuals who are blind using a direct, whole report paradigm and investigated the effects of distracting sounds and walking with the long cane.

1.1 Neuroscience and Psychophysics of the Tactile Working Memory

Burton and Sinclair [9] noted that retention gradients for touch are similar to those of vision and audition, suggesting analogous neural mechanisms of working memory across modalities; however, Oberauer et al. [10] state that (vibro)tactile working memory may suffer from high levels of interference that severely limits tactile working memory capacity and therewith the comparisons between vibrotactile working memory and other forms of working memory. The temporal pattern of neural activation in tactile working memory tasks suggests a two-stage model [11–14]. Apart from the higher associative areas, primary somatosensory regions show activation up to about 1 second after stimulus presentation. This suggests that the primary sensory area is involved in the maintenance of information corresponding to a tactile sensory register as Hill and Bliss [15] proposed based on psychophysical experiments, and similar to that for vision and audition [9].

Before functional neuroimaging studies of tactile working memory became available, evidence for a two-stage model was found in psychophysical data. Basically, different authors consider a first phase related to a fading sensory trace up to several seconds that is unaffected by distracting tasks and has a large capacity, as well as a second, more durable phase up to tens of seconds or even minutes that benefits from rehearsal but has a limited capacity and is negatively affected by distracting tasks. The difference in capacity between the two phases became apparent when discrepancies in results were found for whole and partial report recall paradigms [16]. In whole report recall, participants recall as many items as possible after a retention interval. In a partial report paradigm, participants are required to recall only the part of the presented stimulus set that is cued after presentation of the complete set. Estimations of the working memory capacity are higher for partial report paradigms than for whole report paradigms, indicating that more information is available in the sensory register than consciously available in the short-term store (e.g., [15]).

The first psychophysical experiments to determine the capacity of the tactile working memory are those reported by Bliss et al. [17]. They presented stimuli to up to 12 interjoint locations on the fingers (out of the 24 possible locations, thumbs excluded) in both a whole report and a partial report recall paradigm. For the whole report paradigm, results showed a memory span of about 4.5 items, except for one participant who could chunk items effectively and came to a score of about 7.5 items. In the partial report paradigm, participants received a cue to report either the top, the middle, or the bottom row of eight interjoint positions. The results indicated that more information was available than reported in the whole report paradigm when the cue came in the first 800 ms after presentation. If the cue was delivered after this slot, partial report performance approached that of whole report performance. The authors noted that the results looked remarkably similar to earlier reported results for visual stimuli. But note that in the partial report experiment, the immediate-memory span was only between 3 and 4 stimulus positions, which is below comparable results with visual stimuli. However, this lower level of performance may be caused by experimental choices and lack of training of the participants. Hill and Bliss [15] continued this line of research that resulted in the first description of a two-stage tactile working memory model. Sullivan and Turvey [18] also investigated short-term retention of tactile location (phalanges of the left hand) but included the order of stimulation and retention interval manipulations. Both verbal and nonverbal tasks during the retention interval reduced performance, and forgetting was maximal after 6 seconds. In 2008, Gallace et al. [19] reinitiated the line of work. They noted that tactile working memory studies always used the hands/arms, which have a relatively large representation in the somatosensory cortices, and that "the relative extension of the neural representations across the somatosensory cortex might constrain the duration, the capacity, and/or the access to tactile information presented to different parts of the body surface." Therefore, they presented stimuli to 7 possible locations on the arms, legs, and torso. The task was to report the number of stimulated locations (i.e., spatial numerosity judgment). The results show that for a whole report paradigm, performance was significantly better than chance for displays composed of 1, 2, and 3 stimuli, but not for displays composed of 4, 5, and 6 stimuli. Performance for the partial report paradigm was higher. Auvray et al. [20] employed the same approach with simultaneous spatial stimulation on the fingertips. Their results confirm that partial report scores are above whole report scores and confirm the hypothesis that the fingertips yield a better performance than the rest of the body.

Tactile working memory has also been investigated using other paradigms than (whole or partial) recall. For instance, Klatzky et al. [21] developed a tactile version of the n-back task using vibrotactile stimulation and with the identity of the stimulated finger as stimulus to match. In the n-back task, each new item in a continuous stream should be compared to the item presented n positions ago. With n increasing from 1 to 3, performance showed a steep decline, although still above the chance for $n = 3$.

1.2 Tactile Working Memory Capacity

The different experimental paradigms and performance measures make it difficult to directly compare different studies. A commonly used performance index in psychophysics is the 75% correct threshold or t_{75} that we here operationalize as the number of items that results in a 75% correct score on, for instance, a recall test. Bliss et al. [17] report the data of three participants in experiment 1 [17, figure 3] with an estimated t_{75} of 4 to 5 items, and of four participants in experiment 2 [17, figure 6] with an estimated t_{75} of 2 to 3. Hill and Bliss [15] presented data of five participants [15, figure 3]. For the three participants who were not blind and the one late blind participant, the t_{75} score is 2 to 3, but for the early blind participant it is about 8. Please note that their dataset suffered from a low number of participants (4 + 1) and large learning effects combined with an experimental design in which conditions were not order balance or randomized. Sullivan and Turvey [18] used a fixed number of stimuli in their experimental paradigm. In their experiment 1, each trial consisted of four stimuli. With an unfilled retention interval ("rest"), the mean percentage recalled was 70% when the order of presentation was ignored and 64% when the order was taken into account. Their stimulus set does not allow to infer the t_{75} directly, but based on the 70% correct score for 4 items and assuming a 100% score for 1 item and a linear decline, the estimated t_{75} is 3.5 without temporal order correct and 3.2 with temporal order correct. In their experiment 2, trials consisted of three items and included a direct, whole report condition (retention interval of 0 seconds). Scores were 80% for location correct and 67% for location and order correct. Using the same assumptions, the estimated t_{75} scores are 3.5 and 2.5, respectively. In the data of Gallace et al. [19], the t_{75} (25% error in their data presentation) is 2 to 3 locations in their experiment 1 and just above 2 locations in their experiment 2. These numbers are confirmed in their experiment 3 for both numerosity judgment and position report. The data of Auvray et al. [20] result in an estimated t_{75} of 2 to 3 items for whole report. Although most data are in the same order of magnitude (estimated t_{75} of 3 ± 1 items), it is important to note that performance criteria differed between the experiments. For instance, Gallace et al. [19] and Auvray et al. [20] use numerosity judgment as a performance measure, which is basically a "number correct" score (i.e., *how many?*), ignoring the location of stimulation. Bliss et al. [17] required participants to also process the stimulus location, which is basically a "location correct" score (i.e., *where?*). Apart from number and location correct score and of relevance from an applied perspective, one can additionally incorporate stimulus identity (which is common in visual memory paradigms using letters or pictures) (i.e., *what?*). Recently, Delogu et al. [22] showed the binding of "What" and "Where" in tactile working memory, underlining the validity of investigating number (how many?), location (where?), and identity (what?) performance scores with respect to tactile working memory.

1.3 Relevance for Technology to Support Independent Orientation and Mobility of People with Visual Impairments

Studies into the capacity of the tactile working memory are relevant from an applied point of view, or as Bliss et al. [17] already mentioned, "The results of the present experiments are relevant to the construction of tactile codes for communication using point stimulation of specific anatomical locations as the information-bearing dimension." Presenting information through localized vibrations is gaining interest as a viable option to reduce the threat of perceptual and cognitive overload, for example, in flying [23] and driving [24] and as display modality in so-called ETAs for users with a visual impairment [25, 26]. These devices project objects around the user onto a multipoint tactile display, for instance, worn as a belt around the waist or as a vest covering the torso. A threat display could, for instance, project the location of hostile aircraft onto the three-dimensional sphere of a vibration vest, and an ETA could indicate the direction and distance of obstacles or waypoints to a user who is blind. Numerous experiments demonstrated the viability of this concept to present a single object and the positive effects of offloading vision and audition and reducing cognitive load [27]. However, the presentation of multiple objects and their integration into a coherent spatial picture, for instance, of the layout of obstacles in an environment relies on temporal storage of items in tactile working memory. Practical experience and some more formal evaluations of ETAs for pedestrians who are blind indicate the need to reduce the number of presented objects to prevent information overload, thereby affecting both comfort and walking speed [25, 26, 28–30]. From this applied perspective, it is important to quantify the capacity of the tactile working memory, not only under ideal laboratory conditions but also in relevant use contexts that may, for instance, involve walking, the presence of (non)informative sounds, and the use of a white cane. The presence of (distracting) sounds may affect attention, and attention-modulating activity in sensory regions is critical for the maintenance of sensory information in working memory [31–33]. In addition, the white cane delivers somatosensory cues that may compete for the same processing resources as the tactile display [31, 34].

1.4 The Current Experiment

Previous research found indications for the capacity of the tactile working memory for users who are not blind and under laboratory conditions. The practical value of these studies is limited for the design of ETAs for users who are blind and need to use the ETA under real-world conditions. For instance, we expect that the presence of distracting sounds and walking and using the long cane compete for the same resources and may reduce tactile working memory capacity compared to ideal laboratory conditions. Therefore, we investigate the capacity of the tactile working memory by presenting one to five stimulus patterns (items) on a linear array of five vibrators around the participant's waist. We employ a whole report recall paradigm: directly after presentation, the participant recalls as many items as possible. For each response, we calculate three performance measures: "numerosity" as used by Gallace et al. [19], "location correct" similar to Hill and Bliss [15], and "identity correct" (referring to both location and pattern correct). The latter is the most relevant from an applied perspective, such as when indicating an obstacle's direction (vibration location) and distance (vibration pattern). Fourteen individuals who are blind performed the working memory task under four conditions: with or without noninformative background sounds (recordings from a train station) and either standing still or while walking and using the white cane. These conditions were intended to simulate real-world usage. We expect a working memory capacity in the range of 2 to 4 items based on the previous experiments described in Section 1.3 reporting estimated t_{75} scores of 3 ± 1 items, and we expect a lower capacity with the distracting sounds and during walking. The scores will become lower when the performance measures become stricter in the order of numerosity, location correct, and identity correct.

2 METHODS

2.1 Participants

Participants were nine male and five female students of Bartiméus, a high school for students who have a visual impairment in Zeist, the Netherlands. Eight participants were completely blind: six from birth, one from 11 years of age, and one from 13 years of age. Six participants were visually impaired: two with peripheral vision loss (tunnel vision) with remaining vision less than 5% (according to EN ISO 8596 norm), one with one blind eye and one eye with remaining vision less than 7%, and three with remaining vision from 4% to 8% in both eyes. Their age ranged from 15 to 20 years, with a mean age of 16.6 years. The participants took part on a voluntarily basis and were reimbursed with a 20 Euro gift card. Informed consent forms from the participants and from the parents or caregivers were obtained beforehand. The experiment was approved by the Institutional Review Board (TCPE) of TNO Soesterberg, the Netherlands. Participants were approached via the orientation and mobility instructor of the high school.

2.2 Apparatus

The apparatus included a laptop computer, a vibrotactile display, questionnaires, and an mp3 player and speakers to play environmental noise. The environmental noise was a recording from a train

Fig. 1. Participant wearing the tactile belt over a T-shirt (left) and a control unit with two tactors (right).

station played at 75 to 80 dB. On the laptop computer, a program was run to operate the vibrotactile display and to log the responses of the participants. The experiment took place in a gym room at the school. The gym room was empty apart from a small table for the laptop and the questionnaires (Figure 1). Next to the table stood a chair where the participant could sit. The speakers for the train station sounds were placed in a corner of the gym. Furthermore, walls, benches, and chairs were used to create a walking area of 5 × 5 m. The vibrotactile display (Science Suit, Elitac B.V., the Netherlands; see Figure 1) consisted of a belt made of elastic material and five tactors in a linear constellation. The center-to-center distance between the tactors was 8 cm, which is at least double the spatial acuity of the torso [6] and will minimize interfering effects of perceptual capabilities. The middle tactor was always positioned directly above the belly button on the body midline. The tactors vibrated with a frequency of 130 Hz. On the side of the belt was a control module that connected the tactors via Bluetooth to the laptop. Responses to stimuli were given verbally by the participant and manually entered on the laptop by the experimenter. After completion of a specific condition, the experimenter read out loud the questionnaire for that condition. After completion of the entire experiment, another questionnaire was administered verbally. All questionnaire responses were noted by the experimenter on a paper form.

2.3 Tactile Stimuli

Since we were interested in working memory for numerosity, tactor location, and tactor identity, each of the five vibrators could vibrate in two distinct patterns consisting of either a single vibration (one 100-ms burst followed by a 200-ms pause) or a double vibration (two 100-ms bursts separated with a 100-ms pause). This means that there were 10 unique items (5 tactor locations (where) × 2 vibration patterns (what)). One trial consisted of 1 to 5 items presented sequentially with 300-ms pause in between items (i.e., the total pause after a single vibration is 200 ms + 300 ms). Items in a trial could not have the same tactor location and were always presented from left to right. For each trial length (1 to 5 items), 8 unique trials were randomly chosen from those complying with these constraints, resulting in 40 trials. The items were denoted as follows (this denotation was also used by the participants to give their response): 1, 2, 3, 4, 5 for the single-burst items on tactor locations from left to right (with 3 for the tactor on the midline) and 1-1, 2-2, 3-3, 4-4, 5-5 for the double-burst items on tactor locations from left to right. For instance, the correct response for a trial consisting of 3 items {single burst at location 2, double burst at the middle location, and a double burst at the right-most location} would be {2, 3-3, 5-5}.

2.4 Experimental Design and Data Processing

Each participant completed 40 trials and one questionnaire in each of four different conditions. The order of the conditions was balanced over participants. The four conditions were as follows:

- *No walking/no noise*: The participant stood still (baseline condition mimicking optimal laboratory conditions).
- *Walking/no noise*: The participant walked along the sides of the 5 × 5 m walking area (marked by walls, benches, and chairs) using the white cane but no sounds were played.
- *No walking/noise*: The participant stood still while the train station sounds were played.
- *Walking/noise*: The participant walked along the sides of the 5 × 5 m walking area (marked by walls, benches, and chairs) using the white cane, and the station sounds were played.

2.4.1 *Tactile Working Memory Scores.*

The raw data of the tactile stimuli were preprocessed before we calculated the performance measures for numerosity, tactor location, and tactor identity. For each of the 2,240 trials (14 participants, 4 conditions, 5 different numbers of items, 8 repetitions), we first compared the numerosity of the stimulus (1 to 5) to that of the response (i.e., ignoring the location and pattern). If these matched, the trial was labeled as "numerosity correct," and only these trials were further analyzed. This selection prohibits (high) scores for participants simply calling out each possible item. Of the 2,240 trials, 1,897 were labeled as numerosity correct (85%). For each of these trials, we checked whether the recalled item location(s) matched the presented item location(s) ignoring the item pattern (single or double), which resulted in a "location correct" score of 1 to 5. Finally, for each of the location correct trials, we checked for which of the correct item locations the mentioned item pattern was also correct. This resulted in an "identity correct" score of 1 to 5. Consecutively, performance scores were calculated over the eight repetitions as follows:

- Numerosity, defined as the proportion of numerosity correct trials: Sum of "numerosity correct" / 8.
- Location, defined as the proportion location correct: Sum of "location correct" / number of items (8, 16, 24, 32, 40, for trials with 1, 2, 3, 4, and 5 items, respectively).
- Identity, defined as the proportion location and pattern correct: Sum of "identity correct" / number of items (8, 16, 24, 32, 40, for trials with 1, 2, 3, 4, and 5 items, respectively).

All three performance scores range between 0 and 1. The performance scores were separately analyzed with repeated measures ANOVAs with the following design: *noise* (*no noise, noise*) × *walk* (*standing, walking*) × *number of items* (*1, 2, 3, 4, 5*). Before analysis, data were checked for the ANOVA assumptions, and degrees of freedom were adjusted where needed (Greenhouse-Geisser). No data transformations were applied. The effect size of significant effects is provided as the partial η^2 value. Significant main effects of number of items and significant interactions were further analyzed with a post hoc Tukey test with alpha set at .05.

2.4.2 t_{75}.

To obtain insight into the size of the tactile working memory, we calculated the t_{75} score as the number of items for which the performance score is above the 75% correct threshold for the performance scores that showed a significant effect on the number of items. To obtain the t_{75} score, we made a linear fit to the performance score as the function of the number of items using a least squares loss function. We did the fit aggregated over all data and for the four conditions separately (condition, here and in the following sections, is used for the four noise (2) × walk (2) combinations).

2.4.3 *Questionnaires.*

Subjective rating of the mental effort was provided after each condition on a 21-point scale using the mental demand question from the NASA Task Load Index ("How much mental and perceptual activity did the task require?") [35]. The anchors "not demanding at all" and "very demanding" were verbally provided by the experimenter. The TLX ratings were analyzed with a *noise* (2) × *walk* (2) ANOVA with a Huynh-Feldt correction when needed. After the experiment, six statements on the clarity and comfort of the tactile stimulation and on own performance were rated on 5-point Likert scales (the exact questions and labels are given in Section 3. Finally, several open questions were answered. The descriptive statistics of these ratings and summaries of the open questions are given in Section 3.

2.5 Procedures

The school's mobility trainer approached potential participants and provided them with information about the experiment. When a potential participant showed interest, written experiment information and informed consent forms were emailed to the potential participants and their parents/caregivers, including the contact details of the mobility trainer and the experimenter for additional questions. After signing and returning the informed consent form, a participant was formally enrolled and a date and time for the experiment were chosen. The participant was picked up by the experimenter in the school's canteen and walked to the gym room where the experiment took place. The experimenter outlined the goals and structure of the experiment again and after consent reconfirmation by the participant, the vibrotactile interface was donned above the first layer of clothing (see Figure 1) with the middle tactor just above the belly button of the participant. Subsequently, the vibrotactile items were trained. We explained the items in the context of an ETA application with obstacle direction coded by vibration location and obstacle distance coded as vibration pattern. The location and pattern (identity) coding were trained individually. First, recognition of the item location was trained by activating each of the five tactors from left to right and vice versa. After a tactor had been active, the experimenter told the participant the tactor number. Next, the tactors were activated in random spatial order and the participant was asked to report his or her numbers. During the 10-minute training session, the participant received feedback on performance. The training continued with the single- and double-bursts patterns that were trained in a similar manner. Next, different trials consisting of one to five items were presented, and after each trial, the participant was asked to report the items. In each step, the participant was trained until the set criterion of one error or less in 10 consecutive trials and expressed confidence in his or her performance. After this training, the experiment started. Depending on the condition, the participant was walking with the cane or standing still, and the train station sounds were either played or not. After each stimulus sequence, the participant had to report the items in the order in which they were presented using the coding as described under the preceding tactile stimuli. The participant was told that the sounds (when played) were irrelevant and could be ignored and was advised to start the recall directly after the presentation of the last item. The experimenter logged the response and started the next trial. The time between trials was approximately 15 seconds, depending on how long it took the participant to respond. After completing two conditions, the participant could pause for 5 minutes. In none of the four conditions was feedback on performance given. After completing all conditions, the final questionnaire was administered and the experimenter helped the participant with doffing the tactile display and walked the participant back to the canteen. In total, the experiment lasted approximately 1 hour.

3 RESULTS

All 14 participants completed the experiment. The experimenter noticed that participants tended to stop walking during the tactile presentation. When this happened, the experimenter would repeat the instruction to continue walking, but even then, participants often walked slowly and sometimes stopped ticking with their cane.

3.1 Numerosity

The analysis of the numerosity score showed significant main effects of *walk* ($F(1, 13) = 10.24$, $p < .01$, $\eta_p^2 = .44$) and of *number of items* ($F(2.03, 26.33) = 14.47$, $p < .01$, $\eta_p^2 = .53$),

Table 1. Estimated t_{75} Values for the Different Conditions and Performance Measures

Condition	Numerosity	Identity
Standing/no noise	5.4	4.7
Standing/noise	5.3	2.5
Walking/no noise	4.6	4.1
Walking/noise	3.2	1.6
All conditions	4.5	3.3

and a significant interaction of *noise* × *walk* × *number of items* ($F(2.08, 27.01) = 4.48$, $p < .02$, $\eta_p^2 = .26$). Walking reduced the mean score from .89 (SE = .03) for *standing* to .83 (SE = .04) for *walking*. Scores were also reduced for increasing number of items: means and SE for *1, 2, 3, 4, 5* items: .97 (.01), .92 (.02), .88 (.05), .82 (.04), .71 (.06). The post hoc test showed that the score for five items is significantly lower than the other scores and the score for four items is significantly lower than for one and for two item(s). The three-way interaction confirmed the main effects.

3.2 Location

The ANOVA on the location correct scores showed a significant effect for *noise* ($F(1, 13) = 19.80$, $p < .01$, ${\eta_p}^2 = .60$), and *noise* × *number of items* ($F(2.77, 36.04) = 4.06$, $p < .02$, $\eta_p^2 = .24$). The presence of noise reduced the scores from .94 (SE = .02) for *no noise* to .89 (SE = .02) for *noise present*, and the post hoc results confirm that the effect of noise is present for all numbers of items.

3.3 Identity

The ANOVA on the identity scores showed significant effects for the three main effects: *noise* ($F(1, 13) = 21.94$, $p < .01$, $\eta_p^2 = .63$), *walk* ($F(1, 13) = 5.90$, $p = .03$, $\eta_p^2 = .31$), and *number of items* ($F(2.80, 36.43) = 32.42$, $p < .01$, $\eta_p^2 = .71$). The presence of noise reduced the scores from .84 (SE = .02) for *no noise* to .73 (SE = .04) for *noise present*. During *walking*, the scores were lower (.77, SE = .03) than when *standing still* (.80, SE = .03). Scores decreased with an increasing number of items with means and SE for *1, 2, 3, 4, 5* items: .88 (.03), .88 (.03), .78 (.04), .71 (.03), and .68 (.03); the post hoc test revealed that all levels significantly differ, except for one and two items and for four and five items.

3.4 t_{75}

We calculated the t_{75} for the performance measures with a significant effect of number of items and as a function of condition and pooled over the four conditions. Table 1 presents the results. The condition that resembles a standard laboratory condition for cognitive research is *standing/no noise*.

3.5 Questionnaires

The two-way repeated measures ANOVA *walk* (2) × *noise* (2) showed only a significant main effect of *walk* ($F(1) = 13.60$, $p < .01$, ${\eta_p}^2 = .51$). *Walking* (mean rating 11.2) was perceived as more mentally demanding than *standing still* (mean rating 9.2). The post-experiment statements and their ratings (5-point Likert scale) results are summarized in Table 2. The labels provided with these statements were as follows: 1 = strongly disagree, 2 = disagree, 3 = undecided, 4 = agree, and 5 = strongly agree for questions 1 to 5. The labels for question 6 (I think a made mistakes?) were as follows: 1 = a whole lot, 2 = a lot, 3 = neither a lot nor little, 4 = little, and 5 = very little.

Table 2. Statements and Subjective Ratings (Likert Scale from 1 to 5)

Statement	**Mean (SD)**
I found it easy to differentiate between single and double bursts	3.71 (0.99)
I found it easy to differentiate between the different tactor locations	3.85 (0.95)
I understood the meaning of the vibrations intuitively[1]	4.00 (0.96)
I found the feeling of a vibration comfortable	4.07 (0.47)
I found the feeling of a vibration comfortable, also over a longer period	3.00 (1.10)
I think I made a lot of mistakes	2.64 (0.93)

[1] Note that this refers to the context of an ETA application with obstacle direction coded by vibration location and obstacle distance coded as vibration pattern as explained in the procedure.

Generally, participants indicate that the items were easy to learn and distinguish, both with respect to location and identity (single vs. double burst). The tactile display was comfortable, at least for the duration of the experiment. The open questions and experimenter observations showed the following:

- When first told about the idea of using such a belt in an ETA, for instance, most participants indicated that they would like to receive a lot of information. However, being presented with up to five vibrotactile items, they indicated that five information items would be too much.
- Most participants (10 out of 13, one gave no answer) agreed that the belt should present not more than three items. The remaining participants indicated that the maximum number of items presented could be four or five.
- Fifty percent of the participants were content with the duration of the pause between information items, and the other 50% reported that a longer pause would be better.
- Many participants remarked that the tactors should be more spread out on the tactile interface, as it was hard to differentiate between tactors in some conditions.
- Every participant liked the concept of how the information was presented and found it intuitive. All participants indicated a positive attitude toward such a belt for use in an ETA.

4 DISCUSSION AND RECOMMENDATIONS

4.1 Tactile Working Memory Capacity

The first aim of this experiment was to find the capacity of tactile working memory as reflected by different measures: numerosity judgment, location recall, and location plus identity recall. If we look at the condition that resembles a standard laboratory situation (no walking and no distracting sounds), we find estimated t_{75} values of 5.4 for numerosity and 4.7 for identity. The value for numerosity as estimated in our experiment (5.4) has not been reported before. Numerosity values reported by Gallace et al. [19] and Auvray et al. [20] are between 2 and 3 and thus only half of our values. However, these are experiments employed with participants who were not blind and used a different paradigm. People who are visually impaired differ in sensory cognition [36, 37] and are more used to tactile information [38]. As a result, they often outperform people who are not blind on tactile tasks. In addition, we used a *spatiotemporal* numerosity paradigm (items were presented *sequentially* at different locations), whereas the studies by Gallace et al. [19] used a *spatial* numerosity task in which the items were presented *in parallel* at different locations. Processing in the tactile sense often leads to the integration of stimuli presented closely in time and to altered or even lost spatial information (e.g., Van Erp [5] introduced the term *tactile clutter* for this effect), which may reduce the comprehensibility of the items. In contrast, the tactile sense is relatively good at *temporal* numerosity estimation (stimuli presented sequentially at the same location, which is basically a counting task) and outperforms audition and vision. For instance, the data of Philippi et al. [39] resulting from a temporal numerosity paradigm with ultra-short bursts of vibration (10 ms) indicate an estimated t_{75} value of eight items for temporal numerosity judgment [39, figure 1, 80 ms ISI]. Performance in tactile spatial numerosity judgment may be restricted by (early) spatiotemporal processing of stimulus location in the primary somatosensory cortex rather than by limitations in working memory.

The estimated value for identity (4.7) has not been extensively reported before. Sullivan and Turvey [18] did not use different patterns in their stimuli but report scores for recalled locations in the correct temporal order, which can be considered as a form of stimulus identity beyond location. Based on their data for "location and order correct," we estimated a t_{75} of 2.5 [18, experiment 1] and 3.2 items [18, experiment 2], again lower than our results. The order of stimuli is critical in the tactile *n*-back task where performance for $n = 3$ is still above chance [20].

The results on tactile working memory capacity largely confirm our hypotheses. The capacity under ideal conditions (five items) is actually larger than expected based on the literature (two to four items), and the expected decrease in performance for more strict performance measures is confirmed.

4.2 Effects of Walking and Distracting Sounds

Our second aim was to investigate if and to what extent tactile working memory is affected by conditions that reflect a use case scenario in which information of an ETA is presented on a tactile belt, namely walking with the white cane and the presence of task-irrelevant sounds. Both conditions reduce performance, and both effects are additive. The effect of walking results in a 3% to 7% reduction (depending on the performance measure) and that of sound in a 5% to 11% reduction. Since there is no significant interaction between noise and walk, these effects are additive. The effect of walking and using the cane is in line with our expectations. Multiple resource theory [40, 41] predicts performance reduction when tasks compete for resources. Participants also perceived the tactile working memory task to be more demanding when walking. The observation that participants tended to slow down during stimulus presentation indicates that participants adopted their strategy [42]. However, we did not quantify this experimenter observation in the current experiment.

The effects of the task-irrelevant noise do not significantly affect numerosity scores and the subjective mental effort rating. However, both location and identity scores are impaired by noise, and this is in line with previous studies [43]. Noise may affect performance by redirecting attention away from the current task to the source of noise [31]. This explanation may especially apply to pedestrians who are blind, as they are keen on monitoring ambient sounds for relevant information about their surroundings. Furthermore, the sounds may compete with the vibrotactile information for common perceptual resources [31, 34]. Although the sounds were task irrelevant, the recordings contained speaker announcements. One study (e.g., [43]) showed that especially speech-noise impairs performance in working memory tasks. Additional evidence for shared components in recall stems from multisensory memory benefits [44, 45]. In a relevant context of use (i.e., use during walking and in an environment with distracting sounds), tactile working memory capacity is two items maximum, which is in accordance to the subjective estimation as maximum for an ETA.

Although the participants rated the tactile stimuli to be intuitive and the items easy to differentiate, their experience with the tactile items was, of course, very limited (less than an hour). With more training, processing, and interpreting, the tactile patterns might improve [6] and become automatic [46, 47]. Automated tasks can yield maximized performance since they require fewer resources than a novel or hardly practiced task [40]. As a reference point, to be able to use the white cane efficiently, about 100 hours of training are necessary [48].

These results show that laboratory experiments cannot be simply generalized to real-world settings. Or more concrete: a tactile working memory capacity estimation of about five items in a laboratory environment (numerosity t_{75} in no walking/no noise) may translate to less than two items in an applied setting (identity t_{75} in walking/noise present). The much lower value is confirmed by the participants' evaluation (i.e., the open questions), even though they claimed to prefer receiving much more information before they had actually experienced how difficult it is to process the information under conditions of use. An additional caution should be provided here in that these results may even be lower for other user groups or different operational conditions (e.g., firefighters, military personal, the elderly). Our data were generated by young and healthy users with a visual impairment who may be expected to outperform other populations. Additional demanding conditions (physical stress, task-relevant sounds, etc.) may degrade performance further.

4.3 Limitations

Our overarching aim was to investigate tactile working memory capacity to guide ETA design and applications. We only used 130-Hz vibration as mechanical stimulation, as the human skin is sensitive to many types of mechanical stimulation, including pressure and skin stretch. A legitimate question is to what extent the current conscious recall task is an accurate reflection of the user's mental model of the environment. Memorizing the response coding is a memory task in itself, which may have affected performance. Other methods such as pointing to virtual obstacles in the environment or tapping on the vibrating element may be more intuitive response paradigms. In addition, obstacles were randomly distributed in the current experiment, representing a random obstacle scene. However, objects in many environments are not randomly placed, and their layout may turn a random space into a more predictable place. Working memory performance for a spatial layout that has meaning may be better than for layouts that do not. Both effects may have resulted in an underestimation of tactile working memory capacity. Yet the participants in the experiment were young and fit, and the tactile elements had a large center-to-center distance. Tactile displays in ETAs may not always have such large center-to-center distances, and tactile spatial acuity decreases with age [49]. Another general effect of aging is altered multisensory integration. For instance, older adults may be less able to ignore task irrelevant (auditory) information [50]. These effects may have resulted in an overestimation of tactile working memory capacity.

4.4 Conclusion and Recommendations

Our results show that the capacity of the tactile working memory under ideal conditions is about five items. The scores depend on the performance measure, and they are highest for reporting the number of items and lowest for reporting the location and identity of the items. Auditory distraction and dual tasking lower performance and do so in an additive manner. This leads to the recommendation to use two items as maximum in an applied setting unless users are trained and/or may adopt their strategy, such as lowering their walking speed, without unacceptable costs.

ACKNOWLEDGMENTS

We would like to thank the professionals of Bartiméus (high school for the blind) and particularly mobility trainer Marten van Doorn, and all students who were willing to participate.

REFERENCES

[1] World Health Organization. 2018. Fact Sheet: Blindness and Vision Impairment (October 11, 2018). Retrieved March 11, 2020 from http://www.who.int/en/news-room/fact-sheets/detail/blindness-and-visual-impairment.

[2] D. Dakopoulos and N. G. Bourbakis. 2010. Wearable obstacle avoidance electronic travel aids for blind: A survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 40, 1 (2010), 25–35. DOI: 10.1109/TSMCC.2009.202125

[3] N. Fallah, I. Apostolopoulos, K. Bekris, and E. Folmer. 2013. Indoor human navigation systems: A survey. *Interacting with Computers* 25, 1 (2013), 21–33. `DOI:`10.1093/iwc/iws010

[4] Ó. I. Jóhannesson, R. Hoffmann, V. V. Valgeirsdóttir, R. Unnthorsson, A. Moldoveanu, and Á. Kristjánsson. 2017. Relative vibrotactile spatial acuity of the torso. *Experimental Brain Research* 235, 11 (2017), 3505–3515. `DOI:`10.1007/s00221-017-5073-6

[5] J. B. F. Van Erp. 2005. Vibrotactile spatial acuity on the torso: Effects of location and timing parameters. In *Proceedings of the 1st Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (World Haptics Conference'05)*. IEEE, Los Alamitos, CA, 80–85.

[6] R. Hoffmann, S. Spagnol, Á. Kristjánsson, and R. Unnthorsson. 2018. Evaluation of an audio-haptic sensory substitution device for enhancing spatial awareness for the visually impaired. *Optometry and Vision Science* 95, 9 (2018), 757–765. `DOI:`10.1097/OPX.0000000000001284

[7] J. B. F. Van Erp. 2005. Presenting directions with a vibro tactile torso display. *Ergonomics* 48 (2005), 302–313.

[8] L. R. Elliott, J. B. F. Van Erp, E. S. Redden, and M. Duistermaat. 2010. Field based validation of a tactile navigation device. *IEEE Transactions on Haptics* 3, 2 (2010), 78–87.

[9] H. Burton and R. J. Sinclair. 2000. Attending to and remembering tactile stimuli: A review of brain imaging data and single-neuron responses. *Journal of Clinical Neurophysiology* 17, 6 (2000), 575–591.

[10] K. Oberauer, S. Farrell, C. Jarrold, and S. Lewandowsky. 2016. What limits working memory capacity? *Psychological Bulletin* 142, 7 (2016), 758–799. `DOI:`10.1037/bul0000046

[11] L. Wanga, M. Bodner, and Y.-D. Zhou. 2013. Distributed neural networks of tactile working memory. *Journal of Physiology, Paris* 107 (2013), 452–458.

[12] T. D. Bancroft and P. Servos. 2011. Distractor frequency influences performance in vibrotactile working memory. *Experimental Brain Research* 208 (2011), 529–532.

[13] J. A. Harris, I. M. Harris, and M. E. Diamond. 2001. The topography of tactile working memory. *Journal of Neuroscience* 21 (2001), 8262–8269.

[14] J. A. Harris, C. Miniussi, I. M. Harris, and M. E. Diamond. 2002. Transient storage of a tactile memory trace in primary somatosensory cortex. *Journal of Neuroscience* 22 (2002), 8720–8725.

[15] J. W. Hill and J. C. Bliss. 1968. Modeling a tactile sensory register. *Perception & Psychophysics* 4, 2 (1968), 91–101.

[16] T. D. Bancroft, W. E. Hockley, and P. Servos. 2012. Can vibrotactile working memory store multiple items? *Neuroscience Letters* 514, 1 (2012), 31–34. `DOI:`10.1016/j.neulet.2012.02.044

[17] J. C. Bliss, H. D. Crane, P. K. Mansfield, and J. T. Townsend. 1966. Information available in brief tactile presentations. *Perception & Psychophysics* 1 (1966), 273–283.

[18] E. V. Sullivan and M. T. Turvey. 1974. On the-short-term retention of serial, tactile stimuli. *Memory & Cognition* 2, 4 (1974), 600–606.

[19] A. Gallace, H. Z. Tan, P. Haggard, and C. Spence. 2008. Short term memory for tactile stimuli. *Brain Research* 190 (2008), 132–142.

[20] M. Auvray, A. Gallace, and C. Spence. 2011. Tactile short-term memory for stimuli presented on the fingertips and across the rest of the body surface. *Attention, Perception & Psychophysics* 73 (2011), 1227–1241.

[21] R. L. Klatzky, N. A. Giudice, J. R. Marston, J. Tietz, R. G. Colledge, and K. L. Loomis. 2008. An *n*-back task using vibrotactile stimulation with comparison to an auditory analogue. *Behavior Research Methods* 40, 1 (2008), 367–372.

[22] F. Delogu, W. M. Bergmann Tiest, T. C. W. Nijboer, A. M. L. Kappers, and A. Postma. 2013. Binding in haptics: Integration of "what" and "where" information in working memory for active touch. *PLoS One* 8, 2 (2013), e55606.

[23] L. Eriksson, J. B. F. Van Erp, O. Carlander, B. Levin, H. A. H. C. Van Veen, and J. E. Veltman. 2006. Vibrotactile and visual threat cueing with high G threat intercept in dynamic flight simulation. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, 1547–1551.

[24] J. B. F. Van Erp and H. A. H. C. Van Veen. 2004. Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behaviour* 7, 4–5 (2004), 247–256.

[25] J. B. F. Van Erp, L. C. M. Kroon, T. Mioch, and K. I. Paul. 2017. Obstacle detection display for visually impaired: Coding of direction, distance, and height on a vibrotactile waist band. *Frontiers in ICT* 4 (2017), 23. `DOI:`10.3389/fict.2017.00023

[26] L. Zeng, G. Weber, M. Simros, P. Conradie, J. Saldien, I. Ravyse, J. B. F. Van Erp, and T. Mioch. 2017. Range-IT: Detection and multimodal presentation of indoor objects for visually impaired people. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI'17)*. ACM, New York, NY, Article 54, 6 pages.

[27] J. B. F. Van Erp. 2007. *Tactile Displays for Navigation and Orientation: Perception and Behaviour.* Ph.D. Dissertation, Utrecht University, the Netherlands.

[28] J. Sánchez and M. Elías. 2007. Guidelines for designing mobility and orientation software for blind children. In *Human-Computer Interaction—INTERACT 2007.* Lecture Notes in Computer Science, Vol. 4662. Springer, 375–388. `DOI:`10.1007/978-3-540-74796-3 35

[29] A. D. Heyes. 1984. The Sonic Pathfinder: A new electronic travel aid. *Journal of Visual Impairment and Blindness* 78, 5 (1984), 200–202.

[30] S. Shoval, I. Ulrich, and J. Borenstein. 2001. Computerized obstacle avoidance systems for the blind and visually impaired. In *Intelligent Systems and Technologies in Rehabilitation Engineering*, H. N. L. Teodorescu and L. C. Jain (Eds.). CRC Press, Boca, Raton, FL, 413–448.

[31] J. L. Szalma and P. A. Hancock. 2011. Noise effects on human performance: A meta-analytic synthesis. *Psychological Bulletin* 137, 4 (2011), 682–707. DOI: 10.1037/a0023987

[32] B. Postle. 2006. Working memory as an emergent property of the mind and brain. *Neuroscience* 139 (2006), 23–38.

[33] K. Oberauer. 2009. Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition* 37 (2009), 346–357.

[34] C. D. Wickens. 2008. Multiple resources and mental workload. *Human Factors* 50, 3 (2008), 449–455. DOI: 10.1518/001872008x288394

[35] S. G. Hart and L. E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology* 52 (1988), 139–183. DOI: 10.1016/s0166-4115(08)62386-9

[36] M. A. Heller. 1989. Tactile memory in sighted and blind observers: The influence of orientation and rate of presentation. *Perception* 18 (1989), 121–133.

[37] K. Sathian and R. Stilla. 2010. Cross-modal plasticity of tactile perception in blindness. *Restorative Neurology and Neuroscience* 28, 2 (2010), 271–281. DOI: 10.3233/RNN-2010-0534

[38] S. Millar. 1999. Memory in touch. *Psicothema* 11, 4 (1999), 747–767.

[39] T. G. Philippi, J. B. F. Van Erp, and P. J. Werkhoven. 2008. Multisensory temporal numerosity judgment. *Brain Research* 1242 (2008), 116–125.

[40] C. D. Wickens, D. L. Sandry, and M. Vidulich. 1983. Compatibility and resource competition between modalities of input, central processing, and output. *Human Factors* 25, 2 (1983), 227–248. DOI: 10.1177/ 001872088302500209

[41] P. A. Hancock, T. Oron-Gilad, and J. L. Szalma. 2006. Elaborations of the multiple-resource theory of attention. In *Attention: From Theory to Practice*. A. F. Kramer, D. A. Wiegmann, and A. Kirlik (Eds.). Oxford Scholarship Online, 45–56. DOI: 10.1093/acprof:oso/9780195305722.003.0004

[42] F. Cnossen. 2000. *Adaptive Strategies and Goal Management in Car Drivers*. Ph.D. Dissertation. University of Groningen.

[43] S. Banburry and D. C. Berry. 1998. Disruption of office-related tasks by speech and office noise. *British Journal of Psychology* 89, 3 (1998), 499–517. DOI: 10.1111/j.2044-8295.1998.tb02699.x

[44] F. Botta, V. Santangelo, A. Raffone, D. Sanabria, J. Lupiáñez, and M. O. Belardinelli. 2011. Multisensory integration affects visuo-spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance* 37, 4 (2011), 1099–1109.

[45] J. B. F. Van Erp, T. G. Philippi, and P. J. Werkhoven. 2014. Multisensory memory for object identity and location. In *Haptics: Neuroscience, Devices, Modeling, and Applications*. Lecture Notes in Computer Science, Vol. 8618. Springer, 169—176.

[46] M. A. Heller. 1987. Improving the passive tactile digit span. *Bulletin of the Psychonomic Society* 25 (1987), 257–258.

[47] D. Ostry, N. Moray, and G. Marks. 1976. Attention, practice, and semantic targets. *Journal of Experimental Psychology: Human Perception and Performance* 2, 3 (1976), 326–336. DOI: 10.1037/0096-1523.2.3.326

[48] J. Borenstein and I. Ulrich. 1997. The GuideCane—A computerized travel aid for the active guidance of blind pedestrians. In *Proceedings of International Conference on Robotics and Automation*. IEEE, Los Alamitos, CA. DOI: 10.1109/robot.1997.614314

[49] N. Deshpande, E. J. Metter, S. Ling, R. Conwit, and L. Ferrucci. 2008. Physiological correlates of age-related decline in vibrotactile sensitivity. *Neurobiology of Aging* 29, 5 (2008), 765–773.

[50] A. L. De Dieuleveult, P. C. Siemonsma, J. B. F. Van Erp, and A.-M. Brouwer. 2017. Effects of aging in multisensory integration: A systematic review. *Frontiers in Aging Neuroscience* 9, Article 80 (2017), 1–14. DOI: 10.3389/fnagi.2017.00080

Received December 2018; revised September 2019; accepted November 2019