Tactile Working-Memory Performance of the Blind

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"For most of us, technology makes things easier. For a person with disability, it makes things possible"

Judy Heumann, American Disability Rights Activist and Former Assistant Secretary, U.S.

Abstract

Vibro-tactile electronic travel aids (ETAs) are devices that support independent travel of the blind by indicating obstacles via vibrations. However, it is unclear how much vibro-tactile information can be processed by the user. Furthermore, little is known about the effect of multitasking or noise on the ability to process vibro-tactile information. The present study examined these issues using a continuous report paradigm under four conditions: NoWalking/NoNoise, Walking/NoNoise, NoWalking/Noise and Walking/Noise. Noise indicates the presence of ecologically valid sound and Walking indicates that participants were walking, while using their cane. Forty sequences consisting of one to five vibro-tactile items were relayed to the skin of the abdomen of blind participants. After each sequence, participants had to report the presented vibro-tactile items. It was found that memory accuracy decreased as sequence length increased. In condition NoWalking/NoNoise, memory accuracy significantly decreased after two items, though performance for four items was still about 80%. Yet, if noise or walking was added, accuracy for four items decreased significantly. Interestingly, in condition Walking/Noise recall accuracy was already impaired for one vibro-tactile item. The results of the present study draw attention to the fact that *ETA* designers should take the context of use into account to enhance safety.

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1. Introduction

Vibro-tactile electronic travel aids (*ETAs*) are devices that support independent travel of the blind by indicating obstacles via vibrations. Many *ETA*s have been developed, but only few are commercially available and successful in the market. One important reason for their lack of success is their way of information presentation (Sánchez and Elías, 2007). Often, *ETAs* provide too much information and make independent travel more demanding.

To prevent overloading the user, the information presentation has to be adapted to the limits of human information processing (Yaagoubi and Edwards, 2008). Research (e.g. Bliss, Crane & Townsend, 1966) has shown that tactile working-memory (WM) is smaller than visual WM. However, little is known about the amount of vibro-tactile information that can be processed before memory performance decreases. Moreover, the circumstances in which *ETAs* are used complicate preventing mental overload.

*ETA*s are namely used in addition to the cane and require the user to process feedback from the cane simultaneously with information relayed by the vibro-tactile ETA. Both travel aids relay tactile feedback. Presenting information to the same modality at the same time can lead to poor task performance due to competition for the same resources (Wickens, Sandry, and Vidulich, 1983). However, until now no study examined the effect of simultaneously processing feedback from two different tactile sources on memory performance.

Furthermore, *ETAs* are intended for environments that are characterised by a noisy soundscape. Loud noise has been found to impair WM performance by redirecting attention away from the current task (Szalma and Hancock, 2011). Though the exact effect of noise on the ability to process and recall vibro-tactile information is not known.

The combined effect of walking with the cane and noise on memory performance for vibro-tactile information might be stronger than the individual effects. Multi-tasking can demand more resources than a single task and noise may deplete the amount of resources available. Thus, leaving few resources to process and recall vibro-tactile information (Szalma and Hancock, 2011).

To make sure that the information presented by a vibro-tactile ETA can be processed, stored and acted-upon, the present research addressed the following questions:

1. **How many vibro-tactile items can be presented before recall accuracy decreases significantly?**
2. **Does walking with the cane, while processing vibro-tactile information negatively affect recall accuracy?**
3. **Does the presence of ecologically valid noise negatively affect recall accuracy?**
4. **Does the combination of walking with the cane and noise, as foreseen for operational use, have a stronger effect on recall accuracy for vibro-tactile information, than one of them alone?**

These questions were examined using a continuous report paradigm. Blind participants had to recall vibro-tactile sequences consisting of 1-5 items under four conditions: NoWalking/NoNoise, Walking/NoNoise, NoWalking/Noise and Walking/Noise. Walking indicates that the participant was walking with the cane while vibro-tactile sequences were relayed. Noise indicates the presence of noise, produced by playing a recording of the soundscape of a busy train station at 80dB. The performance measure in each condition was the mean recall accuracy (percentage correct) per sequence lengths. Condition NoWalking/NoNoise addressed the first research question, Walking/NoNoise addressed the second research question, NoWalking/Noise the third research question and Walking/Noise the fourth research question.

Knowledge about the amount of information that can be processed under the aforementioned conditions allows to adapt the information presentation of a vibro-tactile *ETA* accordingly to prevent cognitive and sensory overload.

1.1 Range-IT

The present study took place in the context of the European project *Range-IT* [1]. Within this project, the companies Elitac B.V., Draeger and Lienert, SoftKinetic Sensors, the research institute TNO, the Technical University of Dresden and the University of Ghent work together to develop an *ETA* that increases the range for obstacle detection of the blind to 5 m (the range of the long cane is 1.2 m). It captures information about the surroundings by a Time-of-Flight 3D camera which is analysed in real-time by a portable computer. Decision-making algorithms filter out the relevant information and convert it into vibro-tactile patterns. The vibro-tactile patterns indicate the direction of and distance to obstacles and are transmitted via a vibro-tactile interface to the user's abdomen.

[1] range-it.eu

2. Theoretical Background

"Mobility is the group of skills required by a blind person to enable him to move along both familiar and unfamiliar routes systematically, safely, confidently, with minimal stress, and by himself, as when he wants to do so (Leonard, 1972)".

2.1 Blind Mobility

Walking from one place to another or taking the train are for sighted individuals natural parts of everyday life. Though, as emphasized by the quote above, mobility is a skill which needs to be learned by the blind explicitly.

As the blind lack visual perception, they have to create a cognitive map of the surroundings by inferring information with other senses, which makes independent travel more complex (Strelow, 1985). Touch and hearing are important information sources for the blind to gather information about the surroundings (Warren and Strelow, 1985). A widely used provider of tactile information is the traditional white cane. Individuals navigate by moving the cane from left to right which supplies them with tactile information about objects in their immediate surroundings. However, the range of the cane is only about 1.2 m and it neither provides information about more distant objects, nor objects at waist or head height.

Hearing is utilized to acquire information about the environment by monitoring sound for relevant information. For example, the intensity and type of traffic noise can provide cues about the distance and amount of automobiles on the street, as well as about the traffic situation in general. Another use of hearing that provides information about the surroundings is echo localization. To use this technique, a sound is emitted by tapping the long cane or clicking with the tongue. The reflection of the sound is then used to detect and localize objects (Schenkman and Jansson, 1986). However, echo-location cannot be used at crowded, noisy places as they mask the echo of the emitted sound.

2.2 Electronic Travel Aids

To complement the limits of traditional sources used by the blind to infer information about the surroundings, many researchers and companies have engaged in developing *ETAs*. Over the last decades, an enormous amount of obstacle detection systems have been developed or are still under development that aim to increase walking speed, navigation efficiency and independence of the blind. However, only few products reached or stayed in the commercial market. There are many reasons for the lack of success of *ETAs*, an important one being their way of presenting obstacle information (Sánchez and Elías, 2007). It is unclear how much information can be processed by the user and engineers often do not take the cognitive characteristics of the user into account. However, the threat of information overload is real, both for auditory and tactile presentation (Shoval et al., 2000). Information overload can decrease safety and compromises the usability of an *ETA* (Yaagoubi and Edwards, 2008). Therefore, strict information filters are required, but different systems use different approaches. In the following sections, some approaches implemented in *ETAs* to prevent information overload and adapt the information presentation to the surroundings are discussed.

Sonic Pathfinder

The Sonic Pathfinder (Heyes, 1984) is an outdoor obstacle detection system developed by Anthony Heyes in 1984, which was commercially available for a long time. It relies on an ultrasonic device that utilizes a pulse-echo sonar system to detect obstacles in the surroundings of the user. The *Sonic Pathfinder (SP)* (Heyes, 1984)is worn at the forehead via a headband. This headband comprises five ultra-sonic transducers and three receivers. One receiver points straight ahead and the others to the left and to the right (see Figure 2.1). A microcomputer, worn in a belt pouch around the hip, processes the echoes from obstacles in the walking path and turns them into sonic feedback. In essence, the pitch of the tone decreases as the user gets closer to the obstacle.

The *SP* (Heyes, 1984) implements several decision-making algorithms to make sure that the user only receives the information necessary to avoid bumping into obstacles. The most basic algorithm gives priority to the object central to the user. If there are no obstacles in the direct walking path, the *SP* (Heyes, 1984) conveys information about shorelines, such as walls to the left or right of the traveller. Knowledge about shorelines can facilitate orientation.

What is special about the selection of the information that is displayed by the *SP* is that the

FIGURE 2.1: This picture shows how the headband of the *Sonic Pathfinder* is worn around the head. Retrieved from http://www.sonicpathfinder.org/ on the 16th of October 2015.

range of the presented information changes depending on how fast the user walks. As a result, the device has a range of 2 seconds instead of 2.5 m. The aforementioned approach makes sure that only obstacles which would be encountered within the next 2 seconds are presented. This dynamic information selection mechanism has been implemented to decrease the already high information processing demands of the visually-impaired traveller (Heyes, 1984).

To ensure proper user, a short training by a mobility instructor with the *SP* (Heyes, 1984) (Heyes, 1984) should be followed. Interestingly, a mobility instructor[1] who gave lessons with this device remarked that usually students could use it well and it alleviated safe navigation. However, students did not want to use it publicly as it is worn around the head and makes them stand out as blind even more. On Heye's website it is noted that the *SP* (Heyes, 1984)is no longer commercially available as his eyesight is impaired to such a degree that he can no longer build it.

Although the *SP* (Heyes, 1984) is an obsolete mobility aid, it implements sophisticated information selection mechanisms that aim to prevent information overload. [2]

Navbelt and GuideCane

Navbelt. *Navbelt* (Shoval et al., 2000) can be used instead of the cane or in addition to the cane and was developed at Michigan University. It consists of a belt on which eight ultrasonic

[1] Marten van Doorn, Bartiméus Zeist

[2] Interestingly, Heyes implemented parts of this technology into his car to assist reverse parking. He patented this system in 1983, similar versions are nowadays found in nearly every car and known as parking sensor (Heyes, 2016).

FIGURE 2.2: A user wearing the prototype of *Navbelt* (Shoval et al., 2000).

sensors are mounted and a portable computer that is worn as a backpack. Each sensor covers a range of 15 degree resulting in a 120 degree "view" (see Figure 2.2). The computer processes the input from the sensors and applies algorithms originally developed for obstacle avoidance and navigation of mobile robots. Obstacle information is converted into sonic feedback and transmitted to the user via stereophonic headphones.

Navbelt (Shoval et al., 2000) has two modes: *Guidance Mode* and *Image Mode*. In *Guidance Mode*,the user is guided by acoustic signals in the right direction, around obstacles. Additionally, a travel speed is recommended which depends on the proximity to the closest obstacle. The *Image Mode* aims to paint a sonic picture of the environment. Hence, more detailed information is provided which makes this mode more cognitively demanding. In order to diminish the amount of presented information, only the most important features of the environment are presented, i.e. only objects that are close to the direct travel path.

Navbelt (Shoval et al., 2000) adapts the rate of given information to the user's context. That is, if the user is in a cluttered environment the information transmission rate increases. In contrast, when the user is in an environment with little or no obstacles, only one signal is given every three seconds (Shoval et al., 2000). Four parameters are used to present the information: direction, volume and pitch of the presented audio signal as well as the transmission rate. The direction of the signal indicates the travel direction, the volume represents the closeness of the user to the obstacle and the pitch in *Guidance Mode* depends on the complexity of the travel

environment. The transmission rate of the signals depends on the urgency. If an immediate hazard is detected, the transmission rate increases.

Navbelt (Shoval et al., 2000) was extensively tested during its five-year development period. In one of the tests, participants walked through an artificial environment where various obstacles were distributed using the different modes. The results indicated that the *Guidance Mode* was efficient and resulted in satisfactory walking speeds. As the *Image Mode* provides a more detailed account of the situation it rendered longer initial learning time, as well as more time to understand the signals while walking. This negatively affected the walking speed. Therefore, *Navbelt* (Shoval et al., 2000) was generally found to be efficient in environments with few obstacles, but not in cluttered ones. Even when the information presentation is adapted to the environment, in cluttered environments the information presented by *Navbelt* (Shoval et al., 2000) exceeds the information processing capacity of the user. However, in an environment with few obstacles, *Navbelt* (Shoval et al., 2000) can provide the user with a wide preview of the upcoming travel environment. This was found to be advantageous to the user's travel confidence and facilitated his or her walking pace.

GuideCane. Extensive usability testing of *Navbelt* (Shoval et al., 2000) showed that even after 100 hours of training, users still found it extremely difficult to reach a normal walking pace while interpreting the transmitted signals. Furthermore, it was found that its sonic signals blocked the auditory system. Therefore, an upgrade of the *Navbelt* (Shoval et al., 2000) was developed called *GuideCane* (Ulrich and Borenstein, 2001). The fundamental difference between these two *ETA*s is that *GuideCane* (Ulrich and Borenstein, 2001) indicates the optimal walking path. Thus, users only needs to follow the guidance information, instead of evaluating the information and determine the safe route themselves.

GuideCane (Ulrich and Borenstein, 2001) is a cane with wheels and a little platform in-between where an array of ultrasonic sensors is mounted on (see Figure 2.3). The user walks while pushing GuideCane (Ulrich and Borenstein, 2001) in front of him. *GuideCane* (Ulrich and Borenstein, 2001), just like *Navbelt* (Shoval et al., 2000) has a 120 degree view and scans the environment. If obstacles are detected the on-board computer calculates a safe travel path in real-time and indicates it by steering into the right direction. Evaluations of *GuideCane* (Ulrich and Borenstein, 2001) showed that its tactile feedback is intuitive. Using *GuideCane* (Ulrich and Borenstein, 2001), blind participants could easily reach a normal walking speed even in cluttered environments.

Both systems were developed more than a decade ago and never reached the commercial

market. Amongst others, one reason was that *GuideCane*'s (Ulrich and Borenstein, 2001) sensors were insufficient to detect hanging obstacles or side walk boarders. The reason however why they were described here is their extensive usability testing, which is scarce in research papers about *ETAs* as they mostly focus on the technical components. Furthermore, both systems provide interesting examples of how obstacle information can be adapted to characteristics of the environment and pinpoint to the intuitiveness of tactile feedback.

FIGURE 2.3: A user with the *GuideCane* prototype (Ulrich and Borenstein, 2001)

I-Cane Mobilo

The *I-Cane Mobilo* is an intelligent cane that combines navigation and obstacle detection in one device. It was developed by a multi-professional team and has been commercially available since 2004. The *I-Cane* is a primary mobility aid because it substitutes the traditional cane or a guide dog. Obstacle detection is performed by an ultrasonic sensor that is implemented in the grip of the *I-Cane* (see Figure 2.4). As the *I-Cane* is quite heavy, which hampers panning to scan the environment, it has a wheel on its tip. The *I-Cane*'s scan range is confined by shoulder width and up to 50 cm above the sensor. In the handle of the *I-Cane* resides a tactile arrow that informs the user about obstacles. The user walks with his thumb lying on the tactile arrow (see Figure 2.4) and if an obstacle is detected, the tactile arrow bounces up and down to warn the user (Technologies, 2016).

In combination with a smart phone app, the *I-Cane* can be used as a pedestrian navigation system as well. In such a case, the tactile arrow gives directions to the desired destination by turning left, right or straight ahead. To use the *I-Cane Mobilo* correctly and safely, lessons by a Mobility instructor should be followed. Some schools for the blind in the Netherlands use the *I-Cane* during mobility lessons.

A Drawback of the *I-Cane* is its small tactile interface, as the tactile arrow at times can be hard to feel. Furthermore, its sensor can only detect obstacles in the direct walking path, not diagonal left or right ones. The information presentation of the *I-Cane* for obstacle detection is not adaptive to the situation.

FIGURE 2.4: *I-Cane Mobilo.* The tactile arrow is located above the red on -and off switch. The picture was retrieved from: http://www.i-cane.org/nl/715 on the 16th of October 2015.

In the previous sections, the approach to information presentation of some *ETAs* was discussed. In the next section, it will be outlined how vibro-tactile information can be used to present obstacle information and whether these information is well understood

2.3 Presenting Information via the Tactile Channel

Vibro-tactile information refers to conveying information via vibrations. Little actuators (tactors), with an integrated motor element are commonly used to produce such vibrations. This type of information is not only helpful to the blind, but can be beneficial when other senses are overloaded, or provide valuable orientation cues in case of spatial disorientation (i.e. in the military context see Figure 2.5) (Self et al., 2008).

In the past two decades, a lot of research has been conducted about using tactile information as a sensory substitution for visual information in navigational tasks (e.g. Van Erp, 2005), and especially in the context of obstacle perception in *ETAs* for the blind (e.g. Dakopoulos, Dimitrios and Bourbakis&, Nikolaos, 2009). To be able to avoid obstacles, their position in

FIGURE 2.5: TNO Tactile Torso Display- Tactors integrated in a waistcoat provide spatial information to support situation awareness of helicopter pilots (Self et al., 2008).

3D space needs to be known. Thus, information about their direction and distance needs to be available (Johnson and Higgins, 2006). In the next paragraph, details about how direction and distance can be indicated with vibro-tactile information are provided.

The direction can be indicated using the location of a vibrating tactor. This concept is called "tap-on-the-shoulder" (Erp and Verschoor, 2004) pointing to the fact that the location of a vibration is intuitively interpreted as an external direction. Just like an actual tap on the right shoulder is immediately perceived as the direction "right" (Erp and Verschoor, 2004). For example, a study (Van Erp, 2005) showed that participants could accurately and effortlessly interpret the directions indicated by the location of the vibration on a tactile waist belt in a navigation task. Furthermore, the same study showed that helicopter pilots that wore this waist-belt, could easily translate vibration locations to external directions (Erp et al., 2005).

Up until now, vibro-tactile displays that use the location of vibration as a direction indication have been used for orientation support for astronauts on board of an international space station, or as a more everyday application in cars where vibrators are integrated in the driver's seat to prevent collision with other auto mobiles (Erp and Veen, 2004).

Distance can be coded with temporal rhythm as the skin is susceptible to temporal aspects of stimulation (Erp, 2005). Coding distance by temporal rhythm refers to using the time between two stimuli to indicate distance levels (i.e. 5 m, 10 m). The parking sensor is based on the same principle. The smaller the time between beeps, the closer the car is to an obstacle. How the temporal rhythm of subsequent vibro-tactile signals should be is however not clear from the

literature. For example, Van Erp et al. (2005) compared several distance coding schemes to a control condition in a way-point navigation task. The difference between coding schemes was the pause between subsequent vibrations. It either decreased in relation to the next way-point, or depended on predefined distance levels (certain amount of meters away from the next way-point). In the control condition, the pause between subsequent signals was constant. Effective walking speed was used as the dependent variable, though, the results revealed that difference between the coding schemes and the control condition was not statistically significant.

In summary, vibro-tactile information can be used to indicate spatial information. Especially direction indicated by the tactor location is perceived well. A suitable coding scheme for distance information with temporal rhythm is yet to be found.

To allow for integration of vibro-tactile obstacle information into the cognitive map of the surroundings, a temporary storage system is needed. Namely, tactile WM. In the next section, characteristics of tactile WM, its storage capacity and memory performance are discussed.

2.4 Tactile Working Memory

Working memory is a storage system that temporally holds information. Information in WM is rapidly accessible, however its storage capacity is limited. Models of WM, that specify how sensory information is held, typically include the auditory and visual modality, but neglect the tactile one (e.g. Baddeley 1984). Likewise, there is a great amount of research investigating memory performance for visual and auditory WM (e.g. Luck and Vogel, 1997; Cowan 1998), however only few studies examine memory accuracy for tactile items.

One of the first studies that examined tactile WM was conducted by Bliss et al. (1966). They asked participants to report the location of up to 12 simultaneous brief (100 ms) stimulations to the fingertips of both hands. They found that the immediate span for vibro-tactile stimulation positions was three to four items, this immediate memory declined after 0.8 sec (Crane et al., 1966). An analogous task to quantify the immediate memory span of visual memory yielded a span of four to five items. The authors concluded that tactile memory has similar underlying characteristics as visual memory but a smaller storage capacity (Crane et al., 1966). However, caution needs to be applied when interpreting their results as they had only four participants.

The n-back task is a common measure of WM and Klatzky, Giudice, Tietz, Golledge, and Loomis (2008) set out to examine whether a vibro-tactile n-back would have similar mnemonic underpinnings as the auditory counterpart. They devised a vibro-tactile and an auditory n-back, where n could be 1, 2 or 3. During the vibro-tactile task, participants wore vibro-tactile

stimulators around three of their fingers and if a stimulation of a finger had occurred n steps back as well, they needed to push a button. In the auditory n-back, sounds were delivered in three audio positions (left, middle and right) and participants had to indicate whether the stimuli was presented n steps back to the same location. Results showed a highly correlated pattern of the n-back between auditory and tactile modality. The percentage correct decreased as n increased. However, performance in the vibro-tactile n-back was worse than in the auditory one. These findings also suggest that tactile WM may be smaller than visual or auditory WM .

A recent study by Auvray, Gallace and Spence (2011) examined how many vibro-tactile stimuli can be reported after brief stimulation using a numerosity task. Participants fingertips were stimulated with one to six vibro-tactile activations within a 200 ms interval and participants were asked to report the number of stimulations after each trial. The authors found that performance was above chance-level for up to three stimulations. However, it has to be noted that chance-level was only 17 % and performance for three stimulations was only about 50 % correct.

Auvray et al. (2011) also investigated whether tactile WM performance is higher in a partial-report paradigm than in a full report task. Partial-report implies that not all stimulated locations need to be recalled. Rather, after stimulation, a location on the fingertips is cued and participants are asked whether this location had been stimulated. The authors found that participants performed above chance-level for up to six stimuli in this task. This finding suggests that information which was not available for full report, could be accessed by partial-report.

Taken together, research has shown that tactile WM capacity is about three to four items in a single task in a laboratory environment. However, vibro-tactile *ETA*s are used in more challenging situations, where resource competition may reduce the capacity below three to four items. Typically, *ETAs* are used in addition to the cane. Thus, the user is multi-tasking and has to process information provided by the cane as well as information relayed by the *ETA*. Multi-tasking and its effect on performance are the topics discussed in the next section.

2.5 Multitasking and Performance

A vibro-tactile *ETA* is used in addition to, and thus simultaneously with the cane. This implies, that at the times when the *ETA* provides information, these information has to be processed, stored and acted upon at the same times as the information gathered with the cane.

The Multiple Resource Theory

Since information from the cane, just like from the vibro-tactile *ETA* is tactile in nature, the *Multiple Resource Theory (MRT)* (Wickens et al., 1983) is an obvious theory to consult to make predictions about dual-task performance under modality sharing. Within this theory, the term resource refers to the limited cognitive ability (attentional resources) that can be assigned to meet task demands. The *MRT* (Wickens et al., 1983) evolved based on the finding that performance differences in time-shared tasks could not only be explained by differences in task difficulty or whether one task was favoured over the other. The performance differences were found to be due to different underlying processing structures.

In essence, the *MRT* (Wickens et al., 1983) postulates that there is not one big pool of cognitive resources that can be accessed by tasks until it is empty, but that there are discrete resource dimensions that can be accessed individually. According to the *MRT* (Wickens et al., 1983), there are four discrete resource dimensions, with each two levels. These dimensions are: processing stages, perceptual modalities, visual channel, and processing codes. A schematic representation of the theory is shown in Figure 2.6. If two tasks require the same resource dimension and the same level of the dimension, task performance will be impaired as both tasks compete for the same finite cognitive resources. If different levels of the dimension, for example the auditory and visual level of the perceptual modality are used by two tasks simultaneously, time-sharing performance might not be impaired, though in such a situation, both tasks will still compete for the same perceptual resources. Thus, using two different modalities to present information, does not imply perfect time-sharing performance. If more resources from a certain dimension are demanded for task performance than are available, mental workload will be high (Wickens, 2008).

As can be seen in Figure 2.6 the *MRT* (Wickens et al., 1983) only incorporates the visual and auditory modality, but neglects other modalities such as the tactile one. This shortcoming as well as limitations in other dimensions of the model were addressed by Hancock, Oron-Gilard and Szalma (2006). They extended the model and incorporated the tactile, olfactory and vestibular modality . Hancock et al. (2006) argued that Wickens (1983) chose the auditory and visual modality as these are the predominant perceptual modalities for humans. If the theory would be applied to other species, the dominant perceptual modalities would differ. This remark not only applies to other species, but also to the blind. To be able to apply the *MRT* (Wickens et al., 1983) to the blind, the visual modality would be interchanged with the tactile modality.

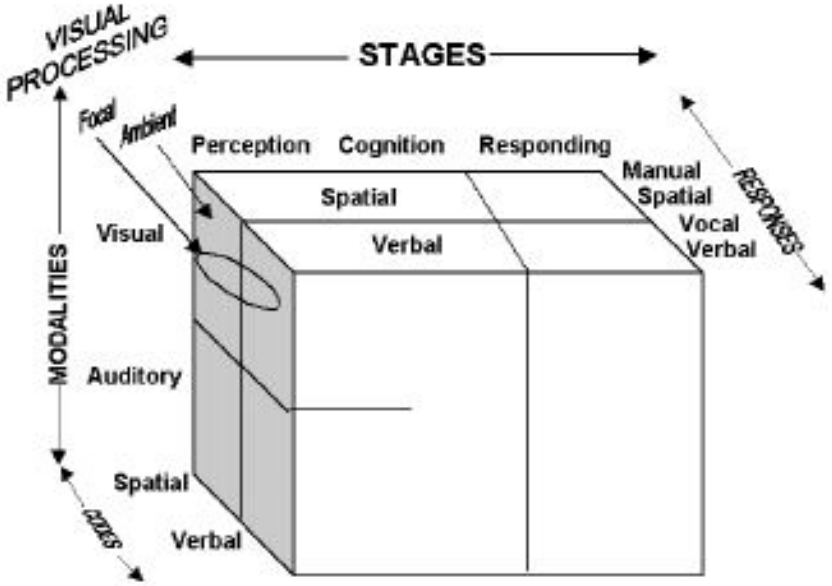

FIGURE 2.6: A schematic depition of the Multiple Resource Theory (Wickens et al., 1983) showing its resource dimension and levels

For the present research, the modality dimension is of particular interest. Since the feedback provided by the cane and the feedback from a vibro-tactile *ETA* is tactile in nature, the *MRT* (Wickens et al., 1983) would predict impaired time-sharing performance in both tasks.

A more modern approach to multi-tasking is *Threaded Cognition*, a theory developed by Salvucci and Taatgen (2008). As *Threaded Cognition* is an extension of the cognitive architecture *Adaptive Control of Thought Rational (ACT-R)* (Anderson, 1996) and thus builds on its assumptions, *ACT-R* (Anderson, 1996) is briefly outlined as well.

ACT-R and Threaded Cognition

ACT-R. *ACT-R* is a unified theory of cognition as well as a modelling environment. It consists of a set of predominantly autonomous modules (resources) which collaboratively achieve cognition (see Figure 2.7). There is a perceptual, a manual, a goal and a problem representation module (representing WM). The perceptual module for example perceives visual and aural input, the goal module controls the task goal and monitors progress towards this goal. The problem representation module temporally holds information necessary for the task.

The central idea of *ACT-R* is that knowledge is represented in two memory systems, declarative -and procedural memory. Declarative memory is the memory system for facts, acquired rules are stored in procedural memory. The production system is the core of *(ACT-R)* as it connects all its modules and can interchange information with them. Skill is acquired by the

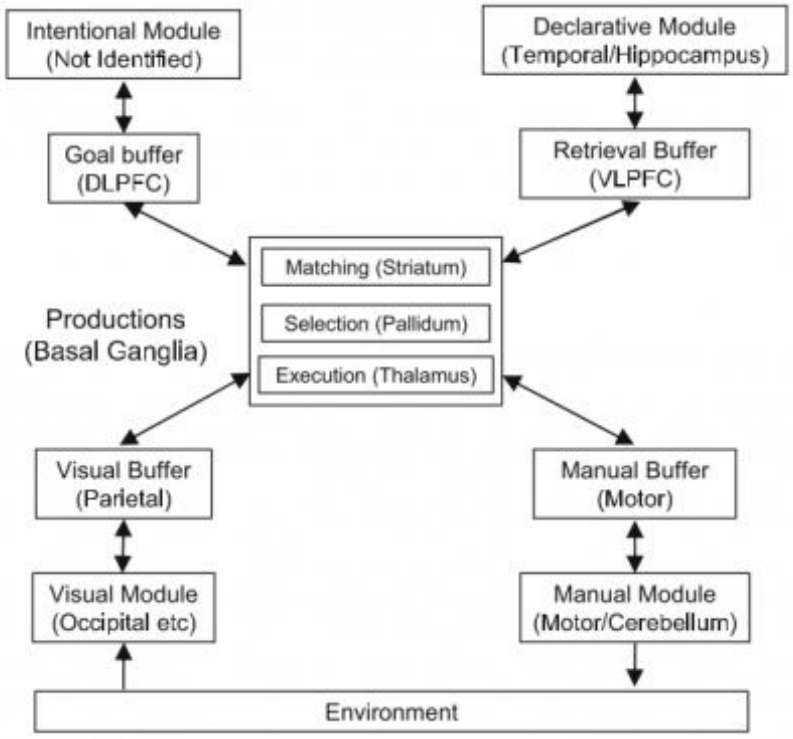

FIGURE 2.7: Schematic depiction of ACT-R (Anderson, 1996) schowing the different modules and how they interact with each other.

mechanism of production compilation. When a task is first practised, the instructions are stored in declarative memory and are interpreted by task general rules. With practice, task general rules gradually turn into task specific production rules. This implies that the procedural and declarative modules are relieved. Instructions no longer have to be interpreted and corresponding facts do not need to be retrieved from declarative memory. Only the production rule needs to be executed.

Threaded Cognition. In ACT-R, tasks are represented as goals which the system aims to satisfy. *Threaded Cognition* (Salvucci and Taatgen, 2008) builds on this assumption, but allows for multiple goals corresponding to multiple tasks. To satisfy these goals, resources are needed, which can only be used in turns by multiple tasks. Thus, if two tasks require the same resource at the same time, a thread to cognition arises. There can be conflicts for the perceptual, procedural, declarative or motor resource.

Acquiring and freeing resources in *Threaded Cognition* (Salvucci and Taatgen, 2008) works according to the greedy/polite policy. This means that if a task requires a resource which is free, it occupies it immediately, though when its done, the process either ends or a result is placed in the buffer that can then be collected by the procedural module. If the buffer is empty, the resource is free again. A resource can only be acquired if a production rule was fired before. If there are more threads waiting to occupy the resource, the least recently processed thread

will go ahead. Threads alternate, which means that one task cannot occupy a resource for the duration of the whole task.

Of course, there is no "tactile module" in *ACT-R*. However, supposing that there would be a "tactile module" which works the same way as the visual module, some predictions can be made with regard to memory performance for vibro-tactile feedback while simultaneously using the cane. The cane, just like the vibro-tactile *ETA* provides tactile information. Thus both tasks, walking with the cane and the vibro-tactile information relayed by an *ETA* share the "tactile module" and probably need it at the same time. Therefore, *Threaded Cognition* (Salvucci and Taatgen, 2008) would predict that when the cane occupies the "tactile module", there is a delay in attending the vibro-tactile information by the tactile interface which causes interference. The tactile resource can only be used by the vibro-tactile *ETA*, if the cane frees it. This will be the case if the information by the cane is processed, placed in the buffer and collected by the procedural module. Vice versa, if the vibro-tactile information occupies the "tactile module", there is a delay in attending the information acquired by the cane. Again, the delay would cause interference.

In summary, both theories, *MRT* (Wickens et al., 1983) and *Threaded Cognition* (Salvucci and Taatgen, 2008) predict that using the cane while processing vibro-tactile information will cause a conflict for the tactile resource. This conflict will impair performance in both tasks.

The usage context of *ETAs* is not only characterised by multi-tasking, but also by a noisy soundscape. Therefore, it is crucial to examine whether noise affects WM performance. In the next section, characteristics of noise are outlined and its effect on performance is discussed.

2.6 Noise and its Diverse Effects on Performance

Noise has a complicated effect on performance that depends on many characteristics of the noise as well as the performance measure used (Szalma and Hancock, 2011). Numerous theories aimed to explain the effect of noise on performance. However, a meta-analysis (Szalma and Hancock, 2011) showed that the *maximal-adaptability theory* (Hancock and Warm, 2003) is especially powerful in explaining the effect of noise on performance. First, this theory is briefly outlined followed by placing the effect of certain noise characteristics on performance in its context.

Noise can be a stressor and according to the *maximal-adaptability theory* (Hancock and Warm, 2003), the effect of stress on performance depends on the adaptability to the stress. The theory takes three components of stress into account when explaining its effect on performance. These are: input, adaptation and output. In the context of noise as stressor, input refers

to the characteristics of the noise as well as to the task performed in the presence of noise. Adaptability describes the individual's mechanisms to cope with noise and output corresponds to the performance level (e.g. accuracy). As a framework, the *maximal-adaptability theory* (Hancock and Warm, 2003) builds on assumptions of an attentional-resource based view. Such a view implies that resources are the fuel needed to meet task demands and this fuel is finite. The amount of resources needed to meet task demands differs across tasks.

Having explained the core idea of the theory, it can be used to explain the diverse effects of noise on performance. With regard to the current research, the noise characteristics task type, noise type, intensity and their impact on performance accuracy are important.

Task type refers to whether the task is a perceptual, cognitive or motor task. Noise has been found to exert the greatest effect on cognitive tasks, especially working-memory ones. According to the *maximal adaptability theory* (Hancock and Warm, 2003) noise demands cognitive resources due to adapting to the presence of noise, i.e. blocking out the noise. As cognitive tasks require more information processing capacity than perceptual or motor tasks, performance in cognitive tasks is affected to a greater extend by fewer available resources due to noise (Szalma and Hancock, 2011).

Noise type refers to the content of noise. For example white noise, often used in experiments, traffic noise, or speech noise. A large body of research (e.g. Jones and Macken, 1995; Banbury and Berry, 1998)) has shown that irrelevant speech impairs WM performance. Using a serial recall paradigm, Salame and Baddeley (1982) showed that WM performance was impaired by irrelevant speech, but not by white noise. The negative effect of irrelevant speech was even present at moderate intensity (55 - 95 dB). They argued that irrelevant speech impairs the memory processes, particularly in the articulatory loop due to phonological similarity of content . Jones, Farrand, Stuart and Morris (1995) did not agree with this line of reasoning and proposed that the changes in pitch characteristics of speech noise are responsible for its disruptive effect on WM performance. Not the phonological similarity of the speech content and the to be recalled content. This hypothesis, called *changing state* (Jones and Macken, 1993), postulates that if noise consists of disconnected entities, it will produce speech-like disruptive effects on WM performance. Evidence for this hypothesis was provided by their finding that noise, with changes in pitch and disconnected sound segments, impaired WM performance. The meta-analysis (Szalma and Hancock, 2011) on the effects of noise on performance confirmed the greater negative effect of speech noise in comparison to white noise. Based on their extensive analysis, Szlama and Hancock (2011) attributed this effect to the distracting character of speech noise on performance and resource competition for attentional resources. Furthermore, they

found that the adverse effect of speech noise was stronger for fragmented noise, in contrast to continuous noise.

Intensity refers to the magnitude of noise typically measured in decibels. Noise can already have a negative effect on memory tasks at moderate intensity (Szalma and Hancock, 2011). A study by Banburry and Berry (1988) examining the effect of different noise types already found an effect for moderate noise intensity. Specifically, they compared the effects of office background noise with speech, office background noise without speech and speech- noise on a prose recall task. The noise level used was 65 dB and its effect was compared to a quiet condition. Recall performance was impaired by speech noise and office noise with speech, but not by office noise without speech . Thus, noise can already have a detrimental effect on memory performance at moderate intensity, though this effect may also depend on the type of noise.

In summary, speech as well as speech-like noise, even at moderate intensity, can impair WM performance due to its demanding character. In public buildings, the environments in which ETAs are used, speech noise may often be present, for example due to speaker announcements. Thus, the presence of such noise may impair WM performance for vibro-tactile information. The negative effect of speech noise on memory performance may be stronger when using the cane as well. Walking with the cane as well as noise require resources, leaving less resources to process and recall virbo-tactile information.

2.7 Experimental Description

Tactile WM can hold about two to three items in a single laboratory task, though it remains unclear what the exact processable amount is.

When using an *ETA* in real life, the circumstances may not be as good as in the laboratory. That is, the surroundings can be noisy and the user is probably multi-tasking, due to using the cane simultaneously with the *ETA*. Such circumstances may reduce memory performance for vibro-tactile information. Engineers and users however often wish to present and receive more information. To resolve these issues and make recommendations about the information presentation of a vibro-tactile *ETA*, the following research questions were addressed:

1. **How many vibro-tactile items can be presented before recall accuracy decreases significantly?**
2. **Does walking with the cane, while processing vibro-tactile information negatively affect recall accuracy?**

3. **Does the presence of ecologically valid noise negatively affect recall accuracy?**
4. **Does the combination of walking with the cane and noise, as foreseen for operational use, have a stronger effect on recall accuracy for vibro-tactile information, than one of them alone?**

The first research question was examined by relaying forty sequences consisting of 1 to 5 vibro-tactile items to the skin of the abdomen of blind participants. After each sequence, participants were required to report the presented vibro-tactile sequence. While receiving and reporting the vibro-tactile sequences, the participant was standing still. To determine the amount of vibro-tactile information that can be presented before recall accuracy drops significantly, the percentage correct (recall accuracy) per sequence length was examined. The effect of using the cane on processing vibro-tactile information was examined using the exact same task, apart from that participants had to walk with their cane while vibro-tactile information was presented. The effect of ecologically valid noise on memory accuracy for vibro-tactile information was examined using the same task, the only difference was that a recoding of the sound scape of a busy train station was played at 80dB. Finally, the combined effect was assessed by requiring participants to recall vibro-tactile information while walking with their cane in the presence of the noise from the train station recording.

In the next chapter, the methods used to answer these questions are outlined in more detail, followed by a description of the results. In the last chapter, the performance outcomes are discussed in terms of their underlying cognitive mechanism as well as their practical implications. Finally, suggestions for future research are given.

3. Method

In the following section, the methods used to answer the research questions are described.

3.1 Participants

Participants were 9 male and 5 female blind pupils. Eight were completely blind and six were visually-impaired with less than 5% vision. The age ranged from 15 - 20, 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 from the parents or caregivers of all participants was obtained beforehand and participants signed an informed consent as well. The experiment was approved by the Ethical Review Board of TNO.

Participants were approached via the Orientation and Mobility instructor of a high school for the blind in the Netherlands.

3.2 Apparatus

The materials used included a laptop computer, a vibro-tactile display, questionnaires, an mp3 player and speakers to play environmental noise. On the laptop computer, a program was run to operate the vibro-tactile display and to log the responses of the participants. The experiment took place in a gym room at *Bartiméus*, Zeist, a high-school for special education for the blind. The gym room was empty apart from a small table, where the laptop computer was placed on as well as the questionnaires. Next to the table stood a chair where the participant could sit on between the conditions. In the left hand corner were four speakers that were connected to the mp3-player. Due to practical reasons they could not be positioned in each corner of the walking area. Furthermore, benches and chairs were used to create together with the walls a walking area (5m*5m).

Tactile Interface

The vibro-tactile display used was a belt made out of elastic material manufactured by the company Elitac B.V.. Five tactors that can relay vibro-tactile information, were positioned on the belt in a linear constellation. The distance between the tactors was 8 cm. On the side of the belt was a control module that connected the tactors via a Bluetooth connection to the operating laptop computer. The tactors vibrated with a frequency of 130 Hz. The tactile interface is shown in Figure 3.1. The outer left tactor was not used in the present research. The remaining five tactors were numbered (1-5) from left to right from the participant's perspective. The tactors were activated by pressing "Start" on the control interface on the laptop-computer. The control interface is shown in Figure 3.5.

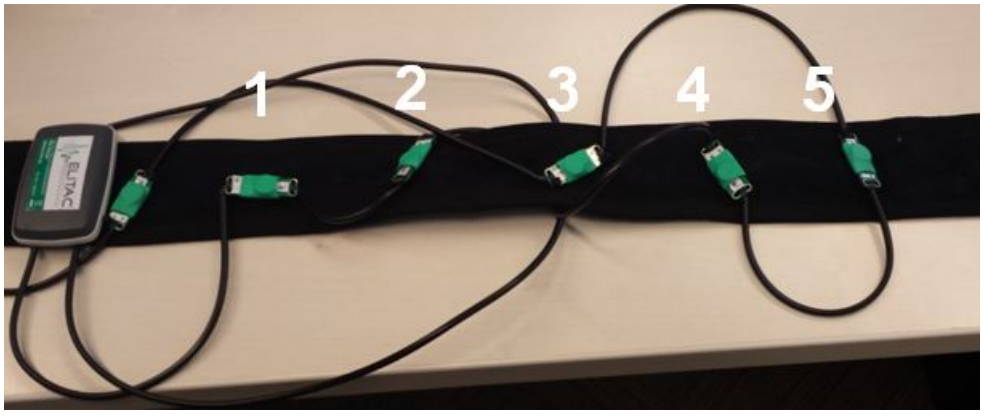

FIGURE 3.1: Tactile Interface. The little green objects are tactors, that transmit vibro-tactile information. Only the ones with a white number above were used. The numbers were used to report which tactors vibrated.

Stimuli

The stimuli were coded in such a way that they could present obstacle information. Thus, two ways of coding information, namely a location coding and temporal coding were used. Within the Range-IT project the location coding is used to indicate the direction of an obstacle and the temporal coding corresponds to the distance of the obstacle. As a result, each stimuli consisted of two coding characteristics. Such a stimuli is called compound message as it comprises two types of information. The compound messages were coded in the extensible mark-up language.

In the experimental task, vibro-tactile sequences consisting of 1, 2, 3, 4 or 5 compound messages were used. The time between compound messages within a sequence was 300 ms. A compound message consisted of a single or double burst relayed by one of the five tactors on the tactile interface (a *burst* is the activation of a tactor).

Table 3.1: Temporal Coding - A line indicates a burst of 100 ms and an empty space denotes the pause between bursts. The temporal coding comprised either a single burst or a double burst. There was a 100 ms break between the two single burst, making up the double burst.

	Time		
	100 ms	200 ms	300 ms
Single Burst	———		
Double Burst	———		———

The single or double burst coding corresponds to the *temporal coding*. One or two burst(s) were delivered in sequence with a pause of 200 ms between bursts. The duration of a burst was 100 ms. The *temporal coding* is shown in Table 3.1.

Within the *location coding*, information is coded with the location on the interface were a burst occurs. There were five possible locations on the tactile interface where bursts could occur (due to the used five tactors). The location coding is shown in Figure 3.2.

Each condition comprised 40 vibro-tactile sequences consisting of 1–5 compound messages. For each sequence length, 8 sets were created where the location of the activated tactor and the temporal pattern was balanced across the sequence. The compound messages that made up the sequence were presented from left to right from the participant's perspective. Hence, the numbers of the tactor in a sequence could only ascend. This means that a sequence such as "1, 2, 5-5, 3" did not exist. A vibro-tactile sequence never contained the same tactor for more than one compound message, for example 1, 1 or 1, 1-1 was not possible. For each condition, the order of the 40 sequences was randomized. The vibro-tactile sequences as well as the order in which they were presented in each condition are shown in Appendix B and Appendix C.

Noise

The environmental noise was a recording from a busy train station played at 75-80 dB. The recoding included speaker announcements.

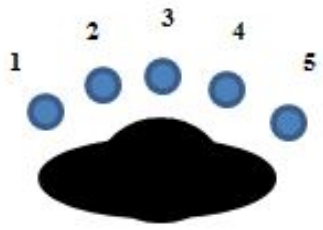

Figure 3.2: Schematic depiction of the location coding. The black form symbolizes the participant's abdomen, the little blue dots indicate the position of the tactors on the participant's abdomen. Positions were reported with the number of the tactors that were activated.

Questionnaire

To get insight into the information presentation of an *ETA* desired by participants (as their are potential users) and their opinion about the used vibro-tactile information presentation, a questionnaire was administered. The first part of the questionnaire consisted of questions about the demographic background of the participant. Furthermore, it comprised six statements about the difficulty to understand the vibro-tactile patterns, the comfort of receiving vibro-tactile stimuli and participants' perception of their own performance. These statements, apart from the last one were rated on a 5-point unipolar Likert-Scale. On this scale, 5 was the maximum that indicated total agreement and 1 was the minimum which indicated total disagreement with the statement. The last rating question "I think I made a lot mistakes" was rated on a different scale. This scale ranged from "a lot mistakes" to "very little mistakes", where the former was anchored with 1 and the latter with 5. Finally, eight open question about the information presentation of the vibro-tactile display and the desired information presentation of an obstacle detection system were asked. The questionnaire can be found in Appendix F.

3.3 Experimental Task and Design

The experiment had a 2(No Walking/ Walking) by 2(No Noise/ Noise) by 5(Sequence length 1-5) within-participants design. The conditions are shown in Table 3.2.

Depending on the condition, the participant was walking with the cane or standing still with or without ecologically valid noise present while executing the experimental task. The experimental task was a vibro-tactile continuous report task. Forty vibro-tactile sequences were relayed via the tactile interface, and after each sequence the participant had to report the sequence in the order in which it was presented. The vibro-tactile sequence was reported by naming the location of the tactor(s) that was (were) active with its (their) number. If a tactor had been active with a single burst, the number would be reported once, and it would be reported twice if it had been active with a double burst. An example of a reported vibro-tactile sequence is: 1, 2-2, 3, 4, 5-5. A schematic display of the experimental task is shown in Figure 3.3. The participant was instructed not to think long about his or her response. The experimenter logged the reported sequences using the control interface (see Figure 3.5) and relayed the next sequence. The time between trials was approximately 15 sec, depending on how long it took the participant to respond.

Tactile memory accuracy for sequence length 1-5 was examined by condition NoWalking/NoNoise.

Table 3.2: Experimental Conditions. Walking indicates that the participant was walking using the white cane while the experimental task was executed. Noise indicates the presence of ecologically valid noise.

NoWalking/NoNoise	Walking/NoNoise
NoWalking/Noise	Walking/Noise

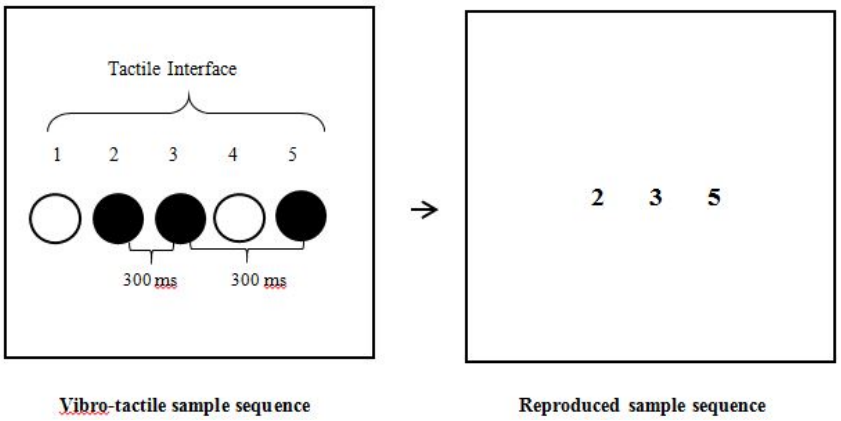

Figure 3.3: Example of the Experimental Task. Left box: A white circel schematizes a tactor and a black circel schematizes a tacors that emits a burst. Right box: An example how the sequence displayed on the right would be reported.

NoWalking indicates that the participant was standing still and NoNoise indicates the absence of environmental sound. The effect of using the cane simultaneously while processing and reporting vibro-tactile sequences was examined by condition Walking/NoNoise. The effect of ecologically valid noise on tactile memory accuracy was assessed in condition NoWalking/Noise, the effect of both combined was examined by condition Walking/Noise. The order of the conditions was balanced across participants to exclude order effects. The order of conditions for each participant can be found in Appendix A.

Measures

For each of the four conditions, two measurements were taken, i.e. recall accuracy (percentage correct) per sequence length and perceived mental effort. Perceived mental effort per condition was measured using the mental effort question from the NASA Task Load Index (Hart, 2006). This question was: "How much mental and perceptual activity did the task require? Please rate this on a scale from 0 to 21. Zero indicates no mental effort at all and 21 indicates very high mental effort." The term mental effort was explained as how much concentration and attention the participant felt that the task demanded.

3.4 Experimental Procedure

Each participant was picked up in the cantine and walked to the gym room where the experiment took place. He or she was greeted and seated and the aim of the *Range-IT* project was described. Next, the experimenter outlined the structure of the experiment, explained the tasks to the participant and asked the demographic questions from the questionnaire. Upon answering the questions, the vibro-tactile interface was fitted above the first layer of clothing around the abdomen of the participant. It was paid special attention to positioning tactor 3 on the belly-button of the participant. Subsequently, the vibro-tactile sequences were trained.

The location and temporal coding were trained individually. First, recognizing the activated tactor 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 of the one that had been active. Next, the tactors were activated in random order and the participant was asked to report their numbers. During the whole training session, the participant received feedback whether his or her responses were correct. After about two training rounds, the training went on with the single and double bursts that were trained in the same manner. Next, different vibro-tactile sequences, (consisting of 1 till 5 compound messages) were presented and after each trial, the participant was asked to report the vibro-tactile sequence. After about two training rounds (participants were trained until they only made about one or zero errors), the experimental task started.

During the training and conditions NoWalking/NoNoise and NoWalking/Noise, the participant stood next to the experimenter's table. This set-up is shown in Figure 3.4. During condition Walking/NoNoise and Walking/Noise, the participant was walking in the walking area. Participants were instructed to walk along the walls and benches that confined the walking area using the cane. After each condition, the participant was asked to rate the mental effort of the past condition. Upon completing two conditions, the participant could pause for 5 min. Then, the two remaining conditions followed. In none of the four conditions feedback about the performance was given. After completing all conditions, the debriefing questionnaire was read out and the experimenter wrote down the answers. (The questionnaire can be found in Appendix G). Finally the participant could add remarks about the experiment and the vibro-tactile interface. In total, the experiment lasted approximately an hour.

FIGURE 3.4: Experimental set-up during the training and condition NoWalking/NoNoise and NoWalkig/Noise. The participant was wearing the tactile interface around the abdomen and standing next to the experimenter's table, while vibro-tactile sequences were relayed.

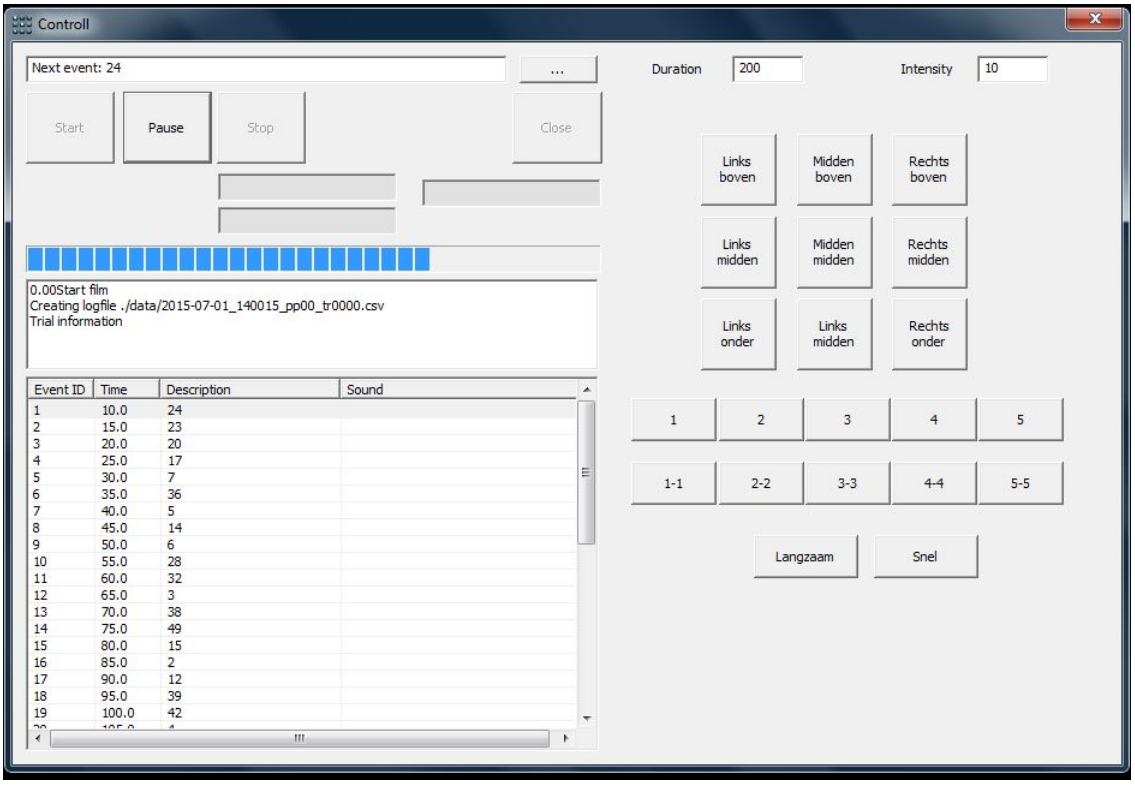

FIGURE 3.5: Control Interface. Vibro-tactile sequences were relayed by pressing *Start*. After the sequence was relayed, the system was pauzed and the participant's response was entered using the number buttons. Then, the next sequence was relayed by pressing *Start* again.

3.5 Scoring of the Data

As the control interface only logged the stimulus number along with the response, the meaning of the stimulus i.e. the vibro-tactile sequence associated with it, had to be entered manually. This was done using Notepad ++. (The stimulus number and the associated sequence can be found in Appendix 4). Subsequently, the data was scored using Microsoft Excel 2010.

The location and temporal coding were scored separately for each vibro-tactile compound message.

Temporal coding

For the temporal coding, both the location of the activated tactor and whether it was a single or double burst needed to be correct to be scored as correct. If the presented sequence was "2-2, 5" and the reproduction was "2-2, 4", "2-2" was scored as correct (with a 1) and "4" as incorrect (with a 0). Next the average score of the sequence was computed. For the example case the average score is 0.5.

Location Coding

The location coding had looser requirements than the temporal coding. Only the location of the reported tactors needed to be correct, but not whether it was a single or double burst. The location coding was scored as follows: If the presented vibro-tactile sequence was "2-2, 5", and the reproduction was "2, 4", the "2" was scored as correct and "5" was scored as incorrect. In a similar vein as for the temporal coding, the average score per sequence was computed. For the example case this would be 0.5.

When the length of the reported sequence did not equal the presented sequence length, the response was regarded as completely incorrect. Thus if the presented vibro-tactile sequence was "1, 2-2, 3, 5" and the reported sequence was "1, 3-3, 4" it was 0% correct.

3.6 Data Analysis

The statistical analysis was conducted in IBM SPSS 22 (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp) and Microsoft Excel 2010, plots were created with R Studio (RStudio Team, 2015). The location and temporal coding were analysed separately. For each condition, the mean accuracy (percentage correct) per sequence length was calculated. This was done by creating five subsets- one for each sequence length- per condition. Per subset, the average score per sequence was added up for each participant and

divided by 8. The sum was divided by 8 as each participant was presented in each condition with each sequence length (1-5) 8 times. The result multiplied by 100 yielded the mean accuracy per sequence length per participant.

Both codings were examined separately to be able to compare performance between coding schemes. First, the outcomes of the temporal coding are reported, followed by the results of the location coding.

Tactile Working Memory Performance

To answer the first research question *How many vibro-tactile items can be presented before recall accuracy decreases significantly"?*, recall accuracy per sequence length in condition NoWalking/NoNoise was examined. A one-way repeated measures ANOVA with the factor sequence length (5 levels) was used to examine whether the performance differed across sequence length. If the omnibus test revealed a significant difference across sequence lengths, repeated contrasts, contrasting each sequence length with the consecutive sequence length (e.g. sequence length 1 with 2, 2 with 3 and so forth) determined where the difference was. To correct for conducting four contrasts, a Bonferroni correction was used and α was adjusted to .0125. Partial eta square (η_p^2) was used to examine the effect size.

The Effect of Multi-Tasking, Noise and both Combined on Tactile WM Performance

To answer the three remaining research questions, *Does walking with the cane, the presence of ecologically valid noise or both combined negatively affect recall accuracy?* a three-way repeated measures ANOVA on recall accuracy with within factor motion (2 levels), noise (2 levels) and sequence length (5 levels), and the interactions between motion*sequence length, motion*noise, noise*sequence length and motion*noise*sequence length was conducted. If there were significant main or interaction effects, pairwise-comparisons with a Bonferroni correction determined where the differences were. For the factor sequence length, repeated contrasts were used to compare each sequence length with the consecutive sequence length. To correct for conducting four comparisons, a Bonferroni correction was used and α was adjusted to .0125. The means are reported along with standard errors. In case of significant differences the mean difference (*Mdiff*) is reported as well. Partial eta square (η_p^2) was used to examine the effect size.

For each sequence length, the mean accuracy was also compared with the respective chance-level performance using z-tests. The chance-level performance for the location coding was calculated as follows: Per vibro-tactile sequence length (1-5) the amount of permutations was computed. 100 divided by that number yielded the chance-level performance: Sequence length 1: 20%, sequence length 2: 9%, sequence length 3: 9%, sequence length 4: 25%, sequence length 5: 50%). For the temporal coding, the location as well as whether the compound message contained a single or double burst needed to be correct. Thus, the chance-level performance was calculated as follows: Sequence length 1: 20% *0.5, sequence length 2: 9%*0.5, sequence length 3: 9%*0.5, sequence length 4: 25%*0.5, sequence length 5: 50%*0.5.

Performance Differences between the Temporal and Location Coding

To examine whether the overall performance differed significantly between the location and the temporal coding, a paired t-test was used.

Perceived Mental Effort

A repeated measures ANOVA with the within factor motion (2 levels) and noise (2 levels) and the interaction motion*noise was conducted to compare the perceived mental effort across conditions. Furthermore, partial eta square (η_p^2) was used as a measure of effect size. If there was a significant effect, a post-hoc comparison with a Bonferroni correction determined where the difference was.

Perceived Difficulty

The mean rating of each statement and its standard deviation were calculated. Furthermore, the answers given to the open questions were summarized.

4. Results

In the following sections, the objective and subjective performance outcomes are described.

4.1 Objective Performance

Before conducting the statistical analysis, the assumptions of the repeated measures ANOVA were examined. It was found that some of the dependent variables violated the assumption of normality. However, within-subjects tests are quite robust against violations of normality and for the present research it was important to be able to analyse interactions. This is not possible with non-parametric tests. Repeated measures ANOVA were conducted as well as the non-parametric equivalent, the Friedman ANOVA. As results were equivalent, the results of the parametric repeated measures ANOVA are reported.

One-way Repeated Meaasures ANOVA. The factor sequence length violated the assumption of sphericity. As the average of both Epsilons (Greenhouse-Geisser and Huynh-Feldt) for the factor sequence length of the temporal coding was greater than .7, the Huynh-Feldt correction was used. The average of both Epsilons of the location coding was smaller than .7, hence the Greenhouse-Geisser correction was applied.

Three-way Repeated Meaasures ANOVA. The within factors motion and noise and the interaction motion*noise violated the assumptions of sphericity as well. Since the average of both Epsilons (Greenhouse-Geisser and Huynh-Feldt) for motion, noise as well as motion*noise of the temporal and location coding was greater than .7, Huynh-Feldt corrections were used.

4.1.1 Tactile Working-Memory Performance

In this section, the recall accuracy for vibro-tactile signals as a function of sequence length in condition NoWalking/NoNoise is described.

Temporal Coding

Figure 4.3 shows the memory performance per sequence length. As sequence length increased, memory performance decreased. For all sequence lengths, memory performance was below perfect performance. For sequence length 1 and 2, a memory performance of 88% was achieved, decreasing to 76% and 75% for sequence length 3 and 4. A substantial drop in performance for sequence length 5 to around 50% can be observed.

A one-way repeated measures ANOVA with the within factor sequence length (5 levels) indicated that memory performance differed significantly across sequence lengths [$F(3.2) = 18.56$, $p = .000$, $\eta_p^2 = .59$]. Repeated contrasts revealed significant differences in memory performance between sequence length 2 and 3 [$F(1) = 8.90$, $p = .011$, $\eta_p^2 = .41$] and sequence length 4 and 5 [$F(1) = 24.58$, $p = .000$, $\eta_p^2 = .65$]. None of the other contrasted consecutive sequence length differed significantly.

Location Coding

Figure 4.6 shows the memory performance per sequence length. As for the temporal coding, performance of the location coding is well below ceiling performance. As sequence length increased, memory performance decreased. For sequence length 1 and 2 a performance of around 90% was achieved. Performance dropped to 80% for sequence length 3 and increased again to 85% for sequence length 4. A substantial drop in memory performance to 65% for sequence length 5 can be observed.

A one-way repeated measures ANOVA with the within factor sequence length (5 levels) indicated that memory performance differed significantly across sequence lengths [$F(2.27) = 9.21$, $p = .001$, $\eta_p^2 = .42$]. Repeated contrasts revealed that recall accuracy for sequence length 4 was significantly higher than for sequence length 5 [$F(1) = 22.27$, $p= .000$, $\eta_p^2 = .63$]. None of the other contrasted consecutive sequence length differed significantly.

4.1.2 The Effect of Multi-Tasking, Noise and both Combined on Tactile Working-Memory Performance

In the following sections, the results concerning the effect of using the cane while processing vibro-tactile information, the effect of the presence of ecologically valid noise as well as the combined effect on recall accuracy are reported.

Temporal Coding

Figure 4.1 shows the mean accuracy per condition of the temporal coding. When standing still, noise in contrast to no noise has a slight negative effect on recall accuracy. Thought, when walking with the cane, noise had a strong negative effect on recall accuracy. In the absence of noise, the negative effect of walking with the cane on recall accuracy was smaller. Thus, noise and walking both seem to affect memory performance. As the lines runs roughly parallel, motion and noise probably do not interact.

Indeed, a three-way repeated measures ANOVA with the within factors motion(2 levels), noise(2 levels) and sequence length(5 levels) showed a significant main effect for motion [$F(1) = 11.92$, $p = .004$, $\eta_p^2 = .48$], a significant main effect for noise [$F(1) = 4.88$, $p = .046$, $\eta_p^2 = .27$], a significant main effect for sequence length [$F(4) = 26.29$, $p = .000$, $\eta_p^2 = .67$], as well as significant interaction effect for motion*noise*sequence length [$F(4) = 4.8$, $p = .003$, $\eta_p^2 = .26$]. The interactions motion*noise, sequence length*noise and sequence length*motion did not significantly affect recall accuracy.

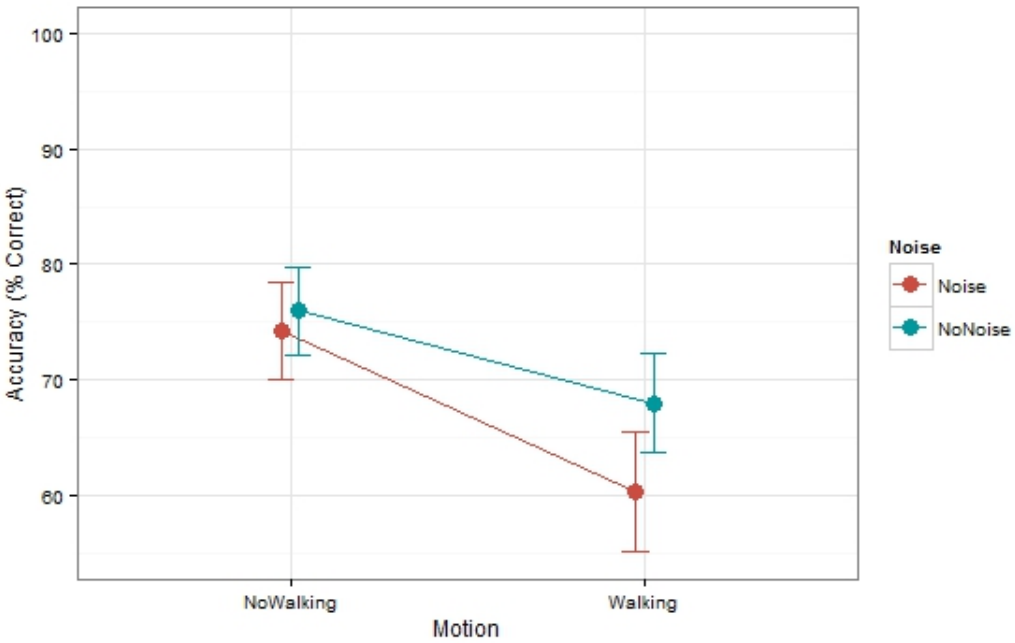

FIGURE 4.1: Temporal Coding - Mean percentage correctly recalled vibro-tactile sequences as a function of walking with the cane, standing still with or without noise. The error bars represent standard errors.

Motion. When the participant was standing still [$M = 75.1 \pm 3.9$], memory performance for vibro-tactile sequences was significantly higher [$Mdiff = 10.9 \pm 3.2$, $p = .004$] in contrast to when walking with the cane [$M = 64.2 \pm 4.4$].

Noise. Without noise [$M = 72.0 \pm 3.6$], recall accuracy was significantly higher [$Mdiff = 4.6 \pm 2.1$, $p = .046$] in contrast to with noise [$M = 67.3 \pm 4.3$].

Sequence Length. Figure 4.2 shows the mean accuracy across sequence lengths. As sequence length increased, recall accuracy decreased. Repeated contrasts indicated significant differences in recall accuracy between sequence length 2 and 3 [$F(1) = 11.66$, $p = .005$, $\eta_p^2 = .47$] and between sequence length 4 and 5 [$F(1) = 13.22$, $p = .003$, $\eta_p^2 = .50$]. There were no significant differences in recall accuracy between the other contrasted consecutive sequence lengths.

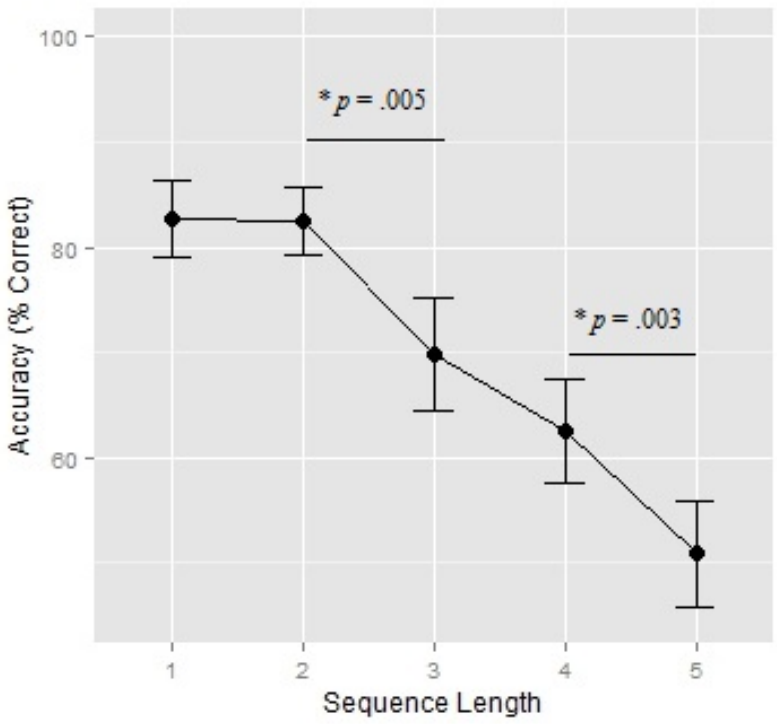

FIGURE 4.2: Temporal Coding - Mean accuracy as a function of sequence length. The error bars represent standard errors. The bars indicate significant differences.

Noise*Sequence Length*Motion. Figure 4.3 shows the recall accuracy per condition per sequence length. In all conditions, recall accuracy decreased as sequence length increased. However, in condition NoWalking/NoNoise, recall accuracy across sequence lengths was higher than in the other conditions. Thought, the performance in condition NoWalking/Noise was similar to the condition NoWalking/Noise, apart from for sequence length 4. Performance in condition Walking/NoNoise was lower than in both aforementioned conditions. Participants' recall the accuracy across sequence length was lowest in condition Walking/Noise.

Multiple comparisons of the interaction Noise*Sequence Length*Motion showed that in the

absence of noise, recall accuracy when standing still was significantly higher in contrast to when walking with the cane for sequence length 4 [*Mdiff* = 19.0 ± 5.7, p = .005]. In the presence of noise, recall accuracy was significantly higher for sequence length 1, 2, 3 and 5 when standing still in contrast to walking with the cane [Sequence length 1: *Mdiff* = 18.8 ± 7.0, p = .019; 2: *Mdiff* = 14.3 ± 4.3, p= .043; 3: *Mdiff* = 18.8 ± 7, p = .019; 5: *Mdiff* = 15.5 ± 6.5, p = .032]. When standing still, noise significantly impaired recall accuracy for sequence length 4 [*Mdiff* = 15.2 ± 4.3, p = .004]. When walking with the cane, noise significantly impaired recall accuracy for sequence length 5 [*Mdiff* = 17 ± 7.0, p = .030]. There were no other significant differences for the three-way interaction.

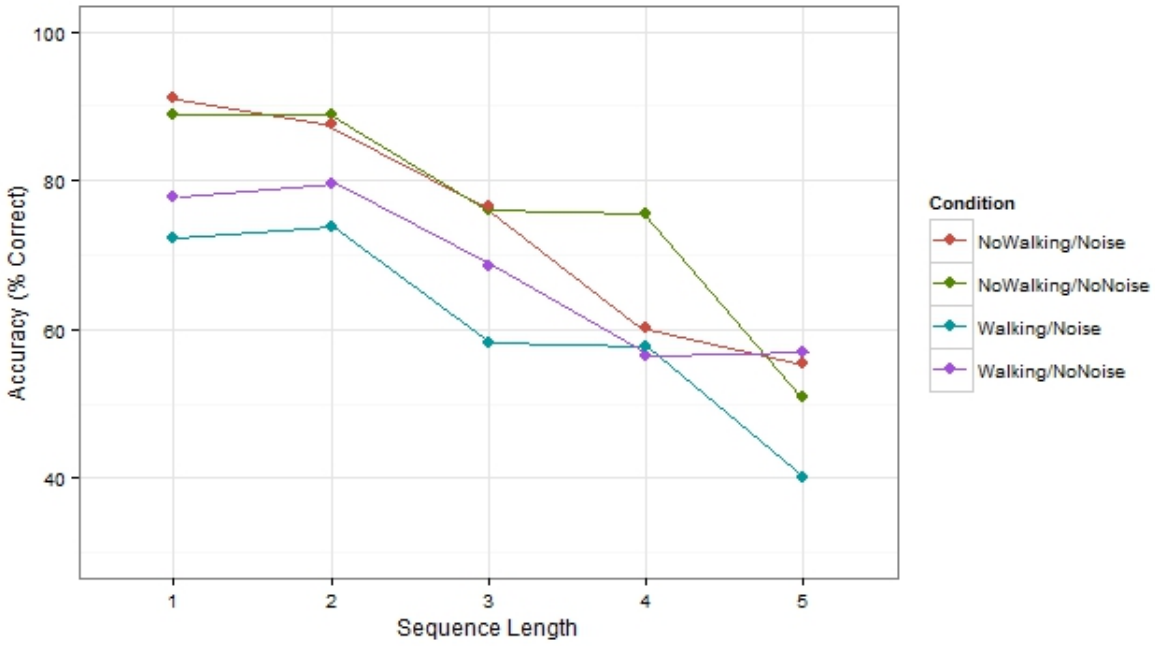

FIGURE 4.3: Temporal Coding - Mean Percentage correctly recalled vibro-tactile sequences as a function of sequence length per condition. To ease interpretation, the errobars are eliminated in this Figure, the same plot with errorbars is shown in Appendix D

Comparison with Chance-level performance

The mean recall accuracy for sequence length 1, 2, 3, and 4 of the temporal coding was significantly higher than would be attained by chance in all conditions. [NoWalking/NoNoise: Sequence length 1: z = 4.17, p = .001, sequence length 2: z = 4.47, p = .001, sequence length 3: z = 3.88, p = .002, sequence length 4: z = 3.36, p = .005. Walking/Noise: Sequence length 1: z = 3.61, p = .003, sequence length 2: z = 4.02, p = .002, sequence length 3: z = 3.52, p = .004, sequence length 4: z = 2.45, p = .030. NoWalking/Noise: Sequence length 1: z = 4.29, p = .001, sequence length 2: z = 4.406, p = .001, sequence length 3: z = 3.88, p = .002, sequence

length 4: $z = 2.63$, $p = .021$. Walking/Noise: Sequence length 1: $z = 3.35$, $p = .005$, sequence length 2: $z = 3.73$, $p = .002$, sequence length 3: $z = 3.07$, $p = .009$, sequence length 4: $z = 2.51$, $p = .03$. Performance for sequence length 5 was not significantly different from chance in all conditions.]

Location Coding

Figure 4.4 shows the mean recall accuracy per condition of the location coding. When standing still, noise in contrast to no noise did not affect recall accuracy. Thought, when walking with the cane, in the presence of noise, recall accuracy decreased. In the absence of noise, walking in contrast to standing still slightly decreased memory performance. Thus, there might be an effect of walking with the cane and noise on recall accuracy. The slight crossing of the lines might indicate an interaction of noise and motion.

A three-way repeated measures ANOVA with the within factors motion(2 levels), noise(2 levels) and sequence length(5 levels) confirmed some of these observations. The analysis indicated a significant main effect for motion [$F(1) = 6.36$, $p = .026$, $\eta_p^2 = .33$], a significant main effect for sequence length [$F(4) = 8.68$, $p = .000$, $\eta_p^2 = .40$], as well as significant interaction effects for motion*noise and motion*noise*sequence length [$F(4) = 5.35$, $p = .001$, $\eta_p^2 = .29$] on recall accuracy. Neither the main effect of noise [$F(2)= 3.28$, $p = .093$], nor the interactions sequence length*noise nor sequence length*motion did significantly affect recall performance for the vibro-tactile sequences.

Motion. When the participant was standing still [$M = 82.9 \pm 4.1$], recall accuracy for the vibro-tactile stimuli was significantly higher [$Mdiff = 7.1 \pm 2.8$, $p =.026$] in contrast to when walking with the cane [$M = 75.8 \pm 3.9$].

Sequence Length. Figure 4.5 shows the mean accuracy as a function of sequence length. As sequence length increased, recall accuracy decreased. Repeated contrasts indicated a significant mean difference in recall accuracy between sequence length 4 and 5 [$F(1) = 9.26$, $p = .009$, $\eta_p^2 = .42$]. There were no significant differences in recall accuracy between the other contrasted consecutive sequence lengths.

Motion*Noise. As can be seen in Figure 4.4, in the absence of noise, walking did not significantly affect recall accuracy in comparison to standing still. However, when noise was present, recall accuracy for the vibro-tactile sequences significantly decreased when walking with the cane in contrast to standing still [$Mdiff = 11.7 \pm 3.3$, $p = .003$]. Neither when walking with the cane, nor when standing still, did noise, in contrast to no noise significantly affect recall accuracy.

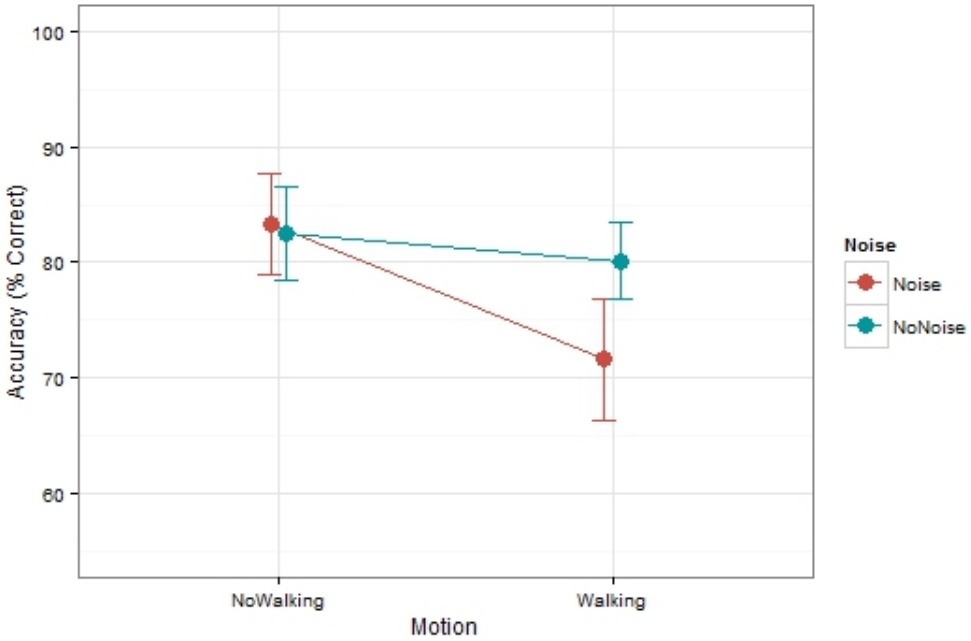

FIGURE 4.4: Location Coding - Mean percentage correctly recalled vibro-tactile sequences as a function of walking with the cane, standing still with or without noise. The error bars represent standard errors.

Noise*Sequence Length*Motion. Figure 4.6 shows the recall accuracy per condition per sequence length. In all conditions, recall accuracy decreased as sequence length increased. Performance was highest in the condition NoWalking/NoNoise. The performance in condition NoWalking/Noise was similar to the aforementioned condition, apart from for sequence length 4. Recall accuracy in condition Walking/NoNoise was lower than in condition NoWalking/NoNoise and NoWalking/Noise. However, participants' memory performance across sequence lengths was lowest in condition Walking/Noise.

Multiple comparisons of the interaction Noise*Sequence Length*Motion showed that in the absence of noise, recall accuracy when walking with the cane was not significantly different in contrast to when standing still for any sequence length. In the presence of noise however, recall accuracy was significantly higher for sequence length 2, 3 and 5 when standing still in contrast to when walking with the cane [Sequence length 2:$Mdiff = 12.5 \pm 3.3$, $p = .002$; 3:$Mdiff = 16.1 \pm 5.1$, $p = .008$; 5:$Mdiff = 17.0 \pm 7.2$, $p = .036$]. When standing still, noise in contrast to no noise led to a significant decrease in recall accuracy for sequence length 4 [$Mdiff = 10.7 \pm 3.8$, $p = .015$]. When walking with the cane, noise in contrast to no noise led to a significant decrease in recall accuracy for sequence length 3 and 5 [Sequence length 3:$Mdiff = 11.0 \pm 4.8$, $p = .038$; 5:$Mdiff = 20.5 \pm 8.1$, $p = .025$]. There were no other significant differences for the three-way interaction.

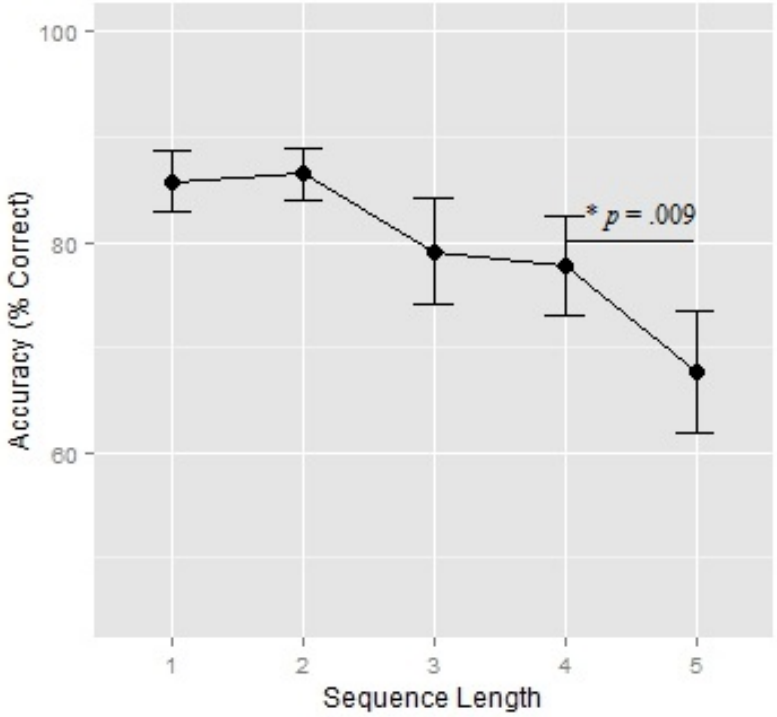

FIGURE 4.5: Location Coding - Mean accuracy as a function of sequence length. The error bars represent standard errors. The bar indicates the significant difference.

Comparison with Chance-level Performance

The mean recall accuracy of sequence length 1, 2, 3, and 4 of the temporal coding were significantly higher than would be attained by chance in all conditions. [NoWalking/NoNoise: Sequence length 1: z = 3.76, p = .002, sequence length 2: z = 4.28, p = .000, sequence length 3: z = -4.29, p = .001, sequence length 4: z = 3.24, p = .006. Walking/NoNoise: Sequence length 1: z = 3.24, p = .006, sequence length 2: z = 4.09, p = .001, sequence length 3: z = 3.8, p = .002, sequence length 4: z = 2.67, p = .019. Noise/NoWalking: Sequence length 1: z = 3.84, p = .003, sequence length 2: z = 4.32, p = .001, sequence length 3: z = 4.07, p = .001, sequence length 4: z = 2.66, p = .020. Walking/Noise: Sequence length 1: z = 3.15, p = .007, sequence length 2: z = 3.67, p = .003, sequence length 3: z = 3.29, p = .005, sequence length 4: z = 2.62, p = .020]. Performance for sequence length 5 was not significantly different from chance in all conditions.]

As both codings showed drops in memory performance after two items, the analysis was also split up between 1 and 2 items vs. 3, 4 and 5 items to compare the effect of the experimental manipulation at both extremes. This analysis can be found in Appendix E.

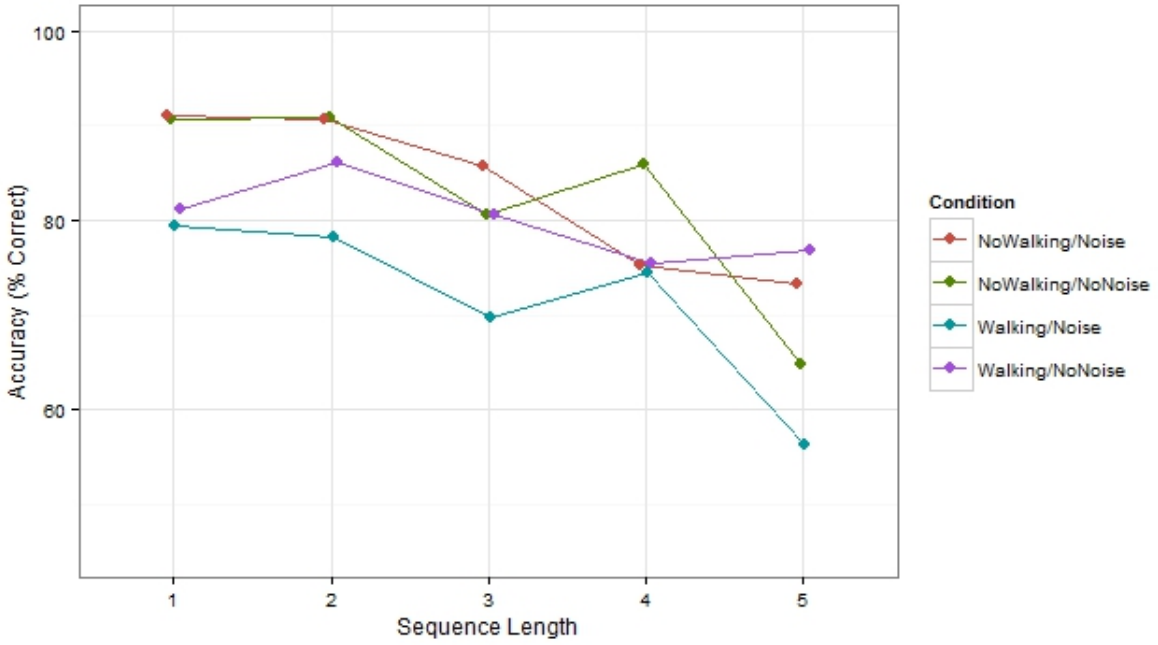

FIGURE 4.6: Location Coding - Mean Percentage correctly recalled vibro-tactile sequences as a function of sequence length per condition. To ease interpretation, the errobras are eliminated in this Figure, the same plot with errorbars is shown in Appendix D

4.2 Differences Between Temporal and Location Coding

Figure 4.7 shows that performance for the location coding was higher than for the temporal coding. A paired sample t-test supported this observation and indicated that recall accuracy of the location coding was significantly higher than of the temporal coding [t (13) = 8.60, p = .000].

4.3 Subjective Performance

In this section, the results of the mental effort rating and the questionnaire are reported.

Perceived Mental Effort

The assumption of normality was met, however, the factors noise, motion and the interaction motion*noise violated the assumption of sphericity. As the average of both (Greenhouse-Geisser and Huynh-Feldt) Epsilons were greater than .7, the Huynh-Feldt correction was used.
Figure 4.8 shows the mean rating per condition. It can be seen that in the absence of noise,

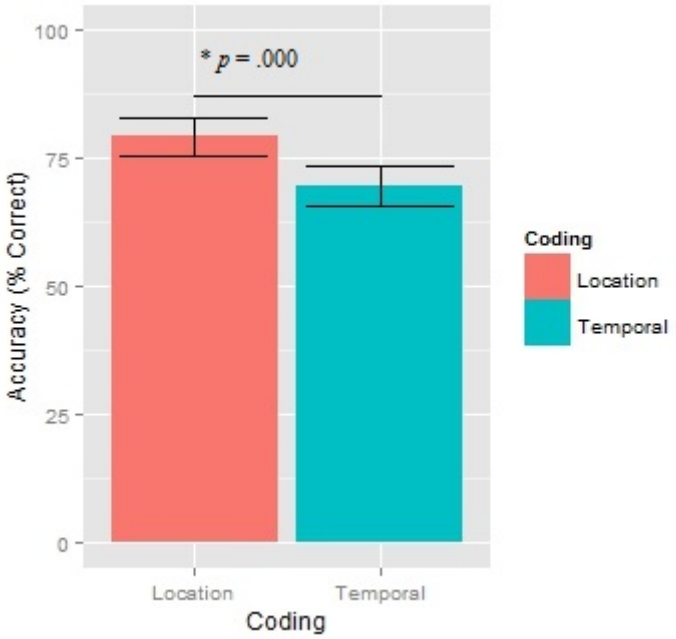

FIGURE 4.7: Overall Performance as a function of location and temporal coding

walking in contrast to standing still was perceived to be more mentally demanding. In the presence of noise, walking was perceived to be slightly more demanding than standing still. As both lines run roughly parallel, noise and motion do not seem to interact. A two-way repeated measures ANOVA with the factor Motion (2 levels) and Noise (2 levels) supported these observations and showed a significant main effect of motion on performance [$F(1)= 13.6$, $p = .003$, $\eta_p^2 = .51$]. However, neither the main effect for noise nor the interaction motion*noise approached significance. Post-hoc paired comparisons showed that walking [$M= 11.2 \pm 1.1$] was perceived as more mentally demanding than standing still [$M = 9.2 \pm 1.3$, $Mdiff = 2 \pm .54$, $p= .003$].

Perceived Difficulty

The perceived difficulty measured by the rating questions of the questionnaire are shown in Table 4.1. Participants were close to agreeing (between nor agree/nor disagree and agree) with the statements that the temporal coding and the location coding was perceptually distinguishable and agreed that the meaning of both codings (indicating direction and distance to an obstacle) was intuitive. Participants agreed that vibro-tactile stimulation was comfortable, but neither disagreed nor agreed that vibro-tactile stimulation over a longer period was comfortable as well. Finally, participants felt that they made few mistakes. Participant's responses to the open questions and informal conversations during the study also gave some insight in the amount of

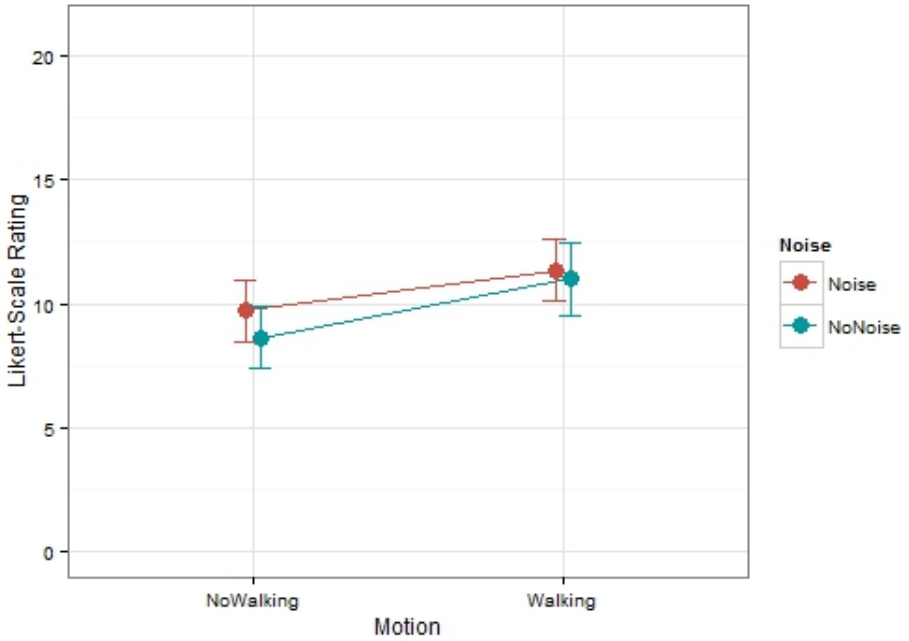

FIGURE 4.8: Perceived mental effort per condition rated on a Likert-Scale ranging from 0 - 21, the former indicates low mental effort and the latter high mental effort

TABLE 4.1: Perceived Difficulty

Statement	Mean Rating	St. Deviation
I found it easy to differentiate between single and double bursts	3.71	.99
I found it easy to differentiate between the different tactor locations	3.85	.95
I understood the meaning of the vibrations intuitively	4.00	.96
I found the feeling of a vibration comfortable	4.07	.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	.93

Note: Rated on a 5-point unipolar Likert-scale with the minimum 1 and maximum 5.

information presentation.

Firstly, most participants (83%) agreed that three items should maximally be presented by an *ETA*. They suggested that this should be information about the left, right and central environment. The remaining participants indicated that the maximum number of items presented could be four or five. Secondly, it became clear that participants who had residual vision had different needs and opinions about an *ETA*. They preferred to receive only information about objects in their direct walking path, while participants who were completely blind desired more information to get a preview of the situation. Furthermore, when first told about the idea of such an *ETA* that would provide an obstacle detection range of 5 m, most participants indicated that they would like to receive a lot of information about the surroundings within 5 m. However, being presented with up to five vibro-tactile items, they indicated that five information items would be too much.

In general, everyone liked the concept of how the information was presented and found it

intuitive. All participants indicated a positive attitude towards such an *ETA*. Warnings about a hanging object was described as the most important feature of such a system. Fifty percent of the participants were content with the duration of the pause between information items, the other 50% reported that a longer pause would be better. Likewise, there were differences in opinions about the ideal level of intensity of the vibro-tactile patterns. Finally, many participants remarked that the tactors should be more spread out on the tactile interface as it was sometimes hard to differentiate between tactors.

Observation

All participants tended to stop walking when the vibro-tactile sequences were relayed. Upon recalling the sequence, they started walking again. However, as the next vibro-tactile sequence came immediately, they stopped walking again. Thus, participants often had to be reminded to continue walking. Still, they then often walked very slowly and stopped ticking with their cane.

5. Discussion

The main goal of the present research was to give advice about the amount of information that should be presented by a vibro-tactile *ETA*. To be able to do so, two important topics were addressed. Namely, tactile WM performance as a function of number of items presented and whether the circumstances in which *ETAs* are used have a negative impact on this performance.

The obtained results however, are not only applicable to the information presentation of a vibro-tactile ETA. In fact, they may provide useful guidelines when using vibro-tactile information in other settings, such as in the military context.

5.1 Tactile Working-Memory Performance

In the current study, the memory performance for two vibro-tactile items was about 90% and still about 80% for four items, which is higher than in Auvray et al.'s (2011) study. In their experiment, participants' fingertips were stimulated for 200 ms with one up to six vibrations simultaneously and participants were asked to judge the numerosity of the stimulations (Auvray et al., 2011). Their participants achieved a percentage correct for one stimuli of 95%, for two stimuli 62%, for three 32% and for four stimuli only 20%.

Furthermore, performance for both codings was significantly higher than chance performance for up to four items. In Auvray et al.'s (2011) study, participants performed above chance for up to three stimuli. An explanation for the obtained performance differences might be the differences in the experimental set-up. In Auvray et al.'s (2011) study there was no pause between items, while the current study used a 200 ms pause between items. In van Erp's (2005) guidelines about using vibro-tactile information, he remarks that multiple vibro-tactile stimuli presented at the same time can cause *tactile clutter*, which may reduce the comprehensibility. Thus, Auvray et al. (2011) might have presented vibro-tactile stimuli too close in time which might have distorted the perception of the stimuli and impaired participant's numerosity judgement. This might especially be the case when many stimuli were presented (Erp, 2002).

Another possible explanation why participants in the current study performed better than those in Auvray et al's (2011) study is that blind people differ in sensory cognition (Sathian and Stilla, 2010). As a result they often outperform the sighted on tactile tasks. Furthermore, the blind are more used to tactile information which might facilitate their tactile memory (Millar, 1999).

The fact that memory performance for five vibro-tactile items was lower than chance-level performance suggests that this amount of vibro-tactile information exceeds the processing capacity of tactile WM. Previous research already suggested that the capacity of tactile WM may be smaller than the visual or auditory counterparts (e.g. Millar, 1999).

Differences Between Temporal and Location Coding

Apart from the difference in memory performance to Auvray et al. (2011), the current study also found diverging results for the temporal coding and the location coding. Memory performance of the temporal coding decreased after two items while recall accuracy for the location coding diminished after four items. This is in line with previous research which showed that information coded by location renders higher performance than information coded by temporal pattern (Erp, 2002).

There are two explanations for these findings. Firstly, the lower performance for the temporal coding is probably due to its stricter requirements for responses to be correct. Both the location of the activated tactor and whether the item was a single or double burst needed to be correct. In contrast, the location coding had looser requirements, only the location of the activated tactor needed to be correct. Secondly, the performance may also have been affected by different underlying memory mechanisms of the location coding. According to Miller (1999) memory for tactile information is inherently spatial and increases if a spatial reference frame is available. The location coding mapped information directly onto spatial locations of the body. This may be advantageous by explicitly providing a reference frame to memorize the vibro-tactile stimulation. The temporal coding lacked such as reference frame.

Nonetheless, the temporal and location coding showed a similar pattern of results across conditions (see Figure 4.3 and Figure 4.6) which suggests that the effects of the conditions on both codings are the same. With increasing complexity, tactile memory performance declined. These findings will be discussed in the following sections, accompanied by possible explanations. The results of both codings are summarized together.

5.2 Tactile Working Memory Performance When Using the Cane

Walking with the cane had a negative effect on participants' memory performance. This is in line with the *Multiple Resource Theory* (Wickens et al., 1983), in particular with the extended version by Hancock (2006), that also includes the tactile modality. Both tasks, reproducing the vibro-tactile sequences and walking with the cane share and thus compete for the tactile modality resource. According to the *MRT* (Wickens et al., 1983), time-shared tasks that use the same level of a resource dimension are less efficient than the use of different levels or even a different dimension. Participants also perceived the tactile WM task to be more demanding when walking with the cane simultaneously, in contrast to standing still. This points to the fact that walking with the cane, while processing and recalling vibro-tactile information, increased mental workload.

The negative effect of walking with the cane on memory performance was especially apparent for longer sequences. A greater amount of vibro-tactile items may also require a greater amount of resources. Thus, with fewer items, enough resources might have been available to execute both tasks. However, processing and recalling four vibro-tactile items might have overloaded the tactile channel and thus resulted in reduced accuracy (Wickens, 2002).

Despite interpreting the results within the *MRT* (Wickens et al., 1983), it should be noted that task performance in time-shared tasks is often more complicated and depends on more factors than the *MRT* (Wickens et al., 1983) includes. Such as: individual WM capacity, the extent to which a skill is practised, or differences in employed performance strategy (Kyllonen and Christal, 1990).

An alternative explanation for the decline in WM performance while walking with the cane could be that due to walking, the tactors might have moved as well. While this might have distorted the perception of the vibro-tactile sequences, and as a result decreased accuracy scores.

Adapting the Strategy

The observation that participants tended to stop in the conditions that required walking, may indicate that in these situations task-load was high. Perhaps participants responded to the increased demand by adopting a less demanding working strategy, namely reducing the walking speed. When moving more slowly, more time is available to process information (Cnossen, 2000).

Furthermore, participants' primary task was to recall the vibro-tactile sequences. Therefore,

they might have allocated more resources to this task. As suggested by Cnossen (2000) the performance in a secondary task might be impaired when one tasks receives priority.

5.3 Tactile Working Memory Performance in the Presence of Noise

Recall accuracy was impaired by noise, specifically for longer sequences. This is in line with previous studies which found that noise impairs WM performance (e.g. Banburry & Berry, 1998). Noise may affect performance by redirecting attention away form the current task to the source of noise (Szalma and Hancock, 2011). This explanation may especially apply to the blind, as they are used to monitoring sounds for relevant information about the surroundings. Furthermore, noise may compete with the vibro-tactile information for common perceptual resources, causing interference in the vibro-tactile WM task (Szlama and Hancock, 2011; Wickens, 2008).

The noise used in the present study was a recoding from a busy train station. This included speaker announcements. Previous research (e.g. Banbury and Berry, 1998) found that especially speech-noise impairs performance in WM tasks. This may be attributed to the demanding character of speech noise which makes it more difficult to ignore than white noise or continuous noise. Thus, speech-noise leaves less resources to execute the WM task, resulting in diminished performance especially for longer sequences (Wickens, 2002).

Although the presence of noise diminished memory performance, participants did not perceive noise to be more demanding than no noise. Such a misconception of mental demand may prevent participants from adapting their working strategy to increased demands. Which may have dangerous consequences, such as missing obstacles, though increased demand might not have been registered introspectively, but participants might still adapt their strategy.

It is important to note that the outcomes of the present study might change if participants would be required to actively process the information included in the noise. For example by requiring participants to distil and report train departure times. This would add a task and attention would needed to be divided between these two tasks (Wickens, 2008). Hence, WM performance may decrease to a greater extend than in the present study. Such a situation might be closer to reality as the announcements at train stations might comprise important information and one would not block out these information.

5.4 Combined Effect on Tactile Working Memory Performance while Using the Cane in the Presence of Noise

In the presence of noise, walking with the cane already impaired memory for few vibro-tactile items. This was not the case when either noise was present or participants were walking with the cane. This, demonstrating that both factors together have a stronger impact than one of them alone. Noise may reduce the amount of cognitive resources available, for example due to coping mechanisms (e.g. blocking out the noise)(Szalma and Hancock, 2011). Furthermore, multi-tasking may demand more resources than solely executing the vibro-tactile WM task as a result of increased difficulty and competition for common resources (Wickens, 2008). However, due to the presence of noise, less resources were available. This resulted in diminished recall accuracy even for short vibro-tactile sequences.

5.5 The Effect of Training

The answers to the open questions and informal conversations with participants suggested that the tactile codings were intuitive and participants found it easy to differentiate between the coding parameters. Furthermore, after two short training rounds, participants had grasped the concept and picked up the vibro-tactile patterns well. As a reference point, to be able to use the white cane efficiently, about 100 hours of training are necessary (Borenstein and Ulrich, 1997). With more training, processing and interpreting the tactile patterns might become automatic (Ostry, Moray and Marks, 1976). Automated tasks can yield maximised performance since they require less resources than a novel or hardly practised task (Wickens et al., 1983). As a result more resources are left to perform another task, such as walking with the cane.

5.6 Recommendations

The main goal of the current study was to formulate recommendations on how much information can be presented in different situations by a vibro-tactile *ETA*. The results indicate that the amount of information presented by an *ETA* should depend on whether the user is walking with the cane or standing still in the presence or absence of noise. Thus, a motion detector and sound level meter could be implemented in the *ETA* and its information presentation could be dynamically adapted to the user's circumstances.

Some studies (e.g. Heyes, 1984)) already acknowledge the need to present information at different rates depending on external parameters. For example, Shoval et al. (2002) varied the information presentation based on the clutteredness of the surroundings. However, usability evaluations showed that their implementation did not result in high performance outcomes. Participants had difficulty understanding the transmitted signals and walked very slowly (Shoval et al., 2000).

Based on the findings of the current study, two separate modes could be developed. An *Exploration-Mode* that is switched on when the user is standing still and presents a larger amount of information and a *Walking-Mode*, that is active when the user is walking and presents less information. In the *Exploration-Mode* up to four vibro-tactile items could be presented. The detection range of the *Exploration-Mode* could be larger, e.g. 5 m, while the detection range of the *Walking-Mode* would be smaller e.g. up to 2.5 m. Thus, slightly larger than the range of the long cane. The *Walking-Mode* could enhance detection of highly relevant obstacles, such as hanging obstacles. In this mode, only important obstacles and no more than two would be presented to prevent mental overload. If loud noise is detected as well, the amount of presented information could be reduced to one items. The *Exploration Mode* could provide a preview of the situation and facilitate orientation in the surroundings when standing still.

A second recommendation is to allow personalization of the intensity of the vibro-tactile stimulation and the pause between consecutive items since there were great differences in opinions of the participants' about both.

5.7 Implications for using Vibro-tactile Information is other Contexts

The findings of the current study may also be relevant outside the *ETA* domain. An important application of vibro-tactile information is the military context (Self et al., 2008). For example, vibro-tactile information can be valuable to pilots in situations where visual perception of the surroundings is compromised due to smoke. Another situation in which vibro-tactile information can be very beneficial is in case of spatial disorientation, for instance on board of helicopters or ships. Such environments may also be characterised by loud noise and information delivered by speakers. Hence, memory for vibro-tactile information might be compromised.

Furthermore, if control panels use haptic feedback, performance for vibro-tactile information delivered by a tactile torso display might be impaired. In these contexts, interaction designers

should be aware that memory for vibro-tactile information might be reduced, though results might be slightly different for sighted individuals.

Yet, it is important to note that not in every multi-tasking situation, memory performance for vibro-tactile information is expected to be impaired. For example, when vibro-tactile information is used to offload the visual channel (e.g. while driving a car), memory for vibro-tactile information won't be impaired as the tactile resource is solely used by one task. In such a situation, vibro-tactile information can be especially useful during multi-tasking to counteract performance degradation due to sensory overload (Erp and Veen, 2004).

Moreover, it would be valuable if models of WM as well as theories about multi-tasking, such as *Threaded Cognition* (Salvucci and Taatgen, 2008) would incorporate the tactile modality as well. This might shed more light onto the underpinnings of performance in multi-modal tasks.

5.8 Limitations of the Current Study

The experimental set-up of the current study has some limitations. In this study, participants were asked to report the presented pattern sequences and the experimenter logged their answers. This way, the experimenter had to remember what they reported to log it. This might have biased the results. Recoding participants' responses might have been a solution to this problem.

Moreover, an additional physiological measure of mental effort could have been used as people might have difficulties to introspectively determine the source of workload and compare different demands against each other. (Wickens et al., 1983). Furthermore, rating scales are subject to social desirability bias (Furnham, 1986).

The normality requirement of the repeated measures ANOVA were not met by all dependent variables. Still, parametric repeated measures ANOVAs were conducted, which assume a normal distribution. This may compromise the statistical validity of the current study.

5.9 Future Research

An interesting experiment for future research would be to incorporate a task with the noise. Such a noise task could for example require participants to recall certain train times from the speaker announcements, as already suggested in section 5.3. Apart from the additional task, the same experimental set-up would be used to examine WM performance. Furthermore, such

a task could act as a measure of mental workload imposed by walking with the cane. This may be done by comparing performance in the noise task (i.e. recalling train departure tasks) when standing still while performing the tactile WM task, with the performance in the noise task when walking with the cane while performing the WM task.

Auvray et al. (2011) found that participants could report up to six vibro-tactile items in a partial report paradigm, while they could only report three items in a full report paradigm. This suggests, that information was retained, but not all information was available for concious report. When using a vibro-tactile *ETA*, this is sufficient as information does not need to be recalled verbally, but only needs to be acted upon. Thus, it would be interesting if a follow up study could replicate these results, when keeping the experimental set-up apart from adopting a partial report paradigm.

To validate the current findings, future research should implement the suggested modes in a vibro-tactile ETA and test them in real environments.

5.10 Conclusion

The findings of this study provide converging evidence that the processing capacity of tactile WM might be small. Furthermore, memory performance for vibro-tactile information might decline in the presence of noise as well as when sharing the perceptual modality with another tactile task. These are important findings that need to be taken into account when implementing vibro-tactile information in a user interface.

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Appendix A

Order of the Conditions per Participant

The numbers indicate the conditions:

1: NoWalking/NoNoise 2: Walking/NoNoise 3: NoWalking/Noise 4: Walking/Noise

1. 1, 3, 4, 2
2. 4, 3, 2, 1
3. 2, 3, 1, 4
4. 4, 3, 1, 2
5. 2, 1, 3, 4
6. 2, 1, 4, 3
7. 1, 4, 2, 3
8. 4, 1, 2, 3,
9. 2, 4, 3, 1
10. 4, 1, 3, 2
11. 2, 4, 1, 3
12. 1, 2, 3, 4
13. 3, 1, 2, 4
14. 3, 2, 1, 4

Appendix B

Vibro-tactile Sequences and their Meaning

The number in front of the colon indicates the stimulus number, i.e. its name. The number sequence after the colon indicate the corresponding vibro-tactile sequence.

17: 2 5

28: 2 3 3 4 4

7: 4

1: 1 1

23: 2 2 3 3 4

33: 1 2 3 3 4 4

38: 1 2 3 3 5

20: 3 3 4

40: 1 1 2 4 4 5

3: 3

48: 1 2 2 3 4 4 5

15: 1 5

26: 1 4 5 5

45: 1 2 3 3 4 4 5 5

13: 2 2 3

2: 4

43: 1 1 2 3 3 4 5 5

6: 5

18: 1 1 2 2

47: 1 1 2 3 3 4 5

44: 1 2 2 3 4 4 5 5

49: 1 1 2 3 3 4 4 5

34: 1 1 3 4 5 5

42: 1 2 2 3 3 4 5 5

27: 2 2 3 5

46: 1 2 2 3 4 5 5

5: 5 5

10: 1

29: 1 3 3 5

32: 2 2 3 4 4 5

30: 1 1 3 5 5

35: 2 2 3 3 4 5 5

24: 2 3 4 4

4: 4 4

16: 3 3 5 5

21: 1 1 3 3 5

12: 4 5 5

14: 1 5 5

39: 1 2 2 4 5 5

36: 1 3 3 4 4 5

Appendix C

Order of vibro-tactile sequences per condition

The vibro-tactile sequence corresponding to the number can be found in Appendix B.

NoWalking/NoNoise

1. 17
2. 28
3. 7
4. 1
5. 23
6. 33
7. 38
8. 20
9. 40
10. 3
11. 48
12. 15
13. 26
14. 45
15. 13

16. 6

17. 2

18. 43

19. 18

20. 47

21. 44

22. 49

23. 36

24. 34

25. 42

26. 27

27. 46

28. 5

29. 10

30. 29

31. 32

32. 30

33. 35

34. 24

35. 4

36. 16

37. 21

38. 12

39. 14

40. 39

Walking/Noise

1. 12
2. 21
3. 3
4. 16
5. 38
6. 49
7. 40
8. 48
9. 15
10. 33
11. 27
12. 7
13. 1
14. 42
15. 46
16. 45
17. 32
18. 30
19. 43
20. 44
21. 6
22. 36
23. 2

24. 5

25. 20

26. 18

27. 17

28. 10

29. 13

30. 28

31. 34

32. 23

33. 47

34. 14

35. 29

36. 39

37. 4

38. 35

39. 24

40. 26

NoWalking/Noise

1. 39
2. 25
3. 28
4. 40
5. 33
6. 1
7. 5
8. 44
9. 18
10. 15
11. 48
12. 47
13. 10
14. 21
15. 30
16. 32
17. 3
18. 43
19. 16
20. 7
21. 34
22. 49
23. 6

24. 23

25. 26

26. 14

27. 38

28. 45

29. 20

30. 4

31. 24

32. 27

33. 17

34. 29

35. 46

36. 42

37. 36

38. 12

39. 2

40. 13

Walking/Noise

1. 24
2. 23
3. 20
4. 17
5. 7
6. 36
7. 5
8. 14
9. 6
10. 28
11. 32
12. 3
13. 38
14. 49
15. 15
16. 2
17. 12
18. 39
19. 42
20. 4
21. 44
22. 45
23. 29

24. 27

25. 10

26. 47

27. 26

28. 40

29. 21

30. 30

31. 35

32. 48

33. 46

34. 1

35. 18

36. 16

37. 43

38. 33

39. 34

40. 13

Appendix D

As the error bars mask the lines, they were not shown in the results section. To show the variability around the mean accuracy nevertheless, they are shown here.

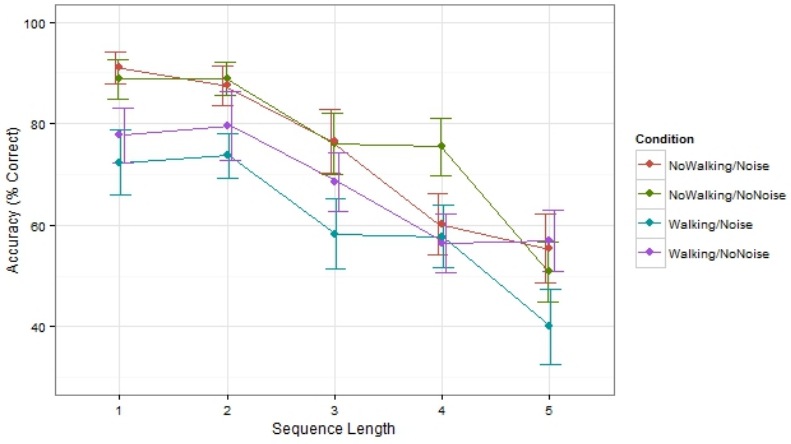

FIGURE 1: Temporal Coding- Percentage correct as a function of sequence length per condition. This Figure shows the same results as Figure 4.3 in the results section. The only difference is that errorbars are displayed as well

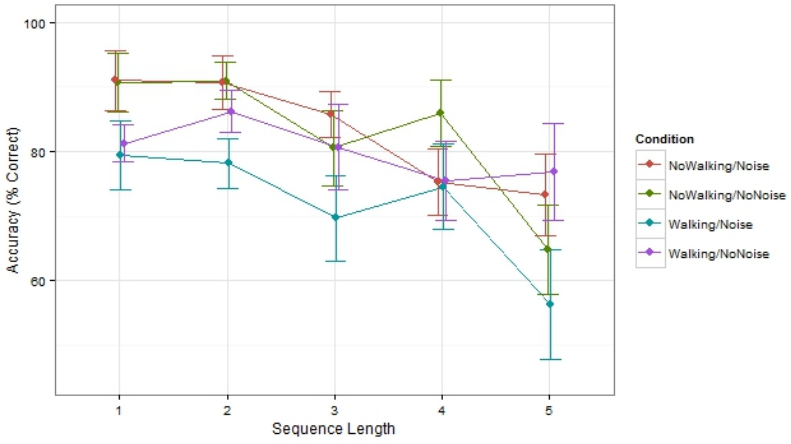

FIGURE 2: Location Coding- Percentage correct as a function of sequence length per condition. This Figure shows the same results as Figure 4.6 in the results section. The only difference is that errorbars are displayed as well

Appendix E

Split-up Analysis Temporal Coding

Since there was a drop in recall accuracy after sequence length 2, the analysis was also split up after sequence length 2 to examine the effects of motion, noise sequence length and the interaction effects at both extremes.

Sequence Length 1-2

A 2(motion)*2(noise)*2(sequence length 1 and 2) repeated measures ANOVA showed a significant main effect for motion [$F(1) = 11.51$, $p = .005$, $\eta_p^2 = .47$]. The main effect for noise, sequence length, and the interaction effect for noise*motion*sequence length disappeared when only looking at sequence length 1 and 2. The other interactions stayed non-significant. The significant effects were in the same direction as in the full analysis above.

Sequence Length 3-5

A 2(motion)*2(noise)*3(sequence length 3, 4, 5) repeated measures ANOVA showed a significant main effect for motion [$F(1) = 7.10$, $p = .019$, $\eta_p^2 = .35$], a significant main effect for noise [$F(1) = 6.70$, $p = .023$, $\eta_p^2 = .34$], a significant main effect for sequence length [$F(4) = 16.85$, $p = .000$, $\eta_p^2 = .57$], as well as significant interaction effect for motion*noise*sequence length [$F(2) = 9.01$, $p = .001$, $\eta_p^2 = .41$]. The other interactions were not significant.

Sequence Length. When only examining sequence length 3-5, the difference in recall performance between sequence length 3 and 4 [$F(1)= 8.05$, $p = .014$, $\eta_p^2 = .38$] became significant. The difference in recall accuracy between sequence length 4 and 5 [$F(1)= 13.22$, $p = .003$, $\eta_p^2 = .50$] was still significant. The longer sequences yielded a significantly worse recall accuracy. The significant differences for motion, noise and Motion*noise and sequence length were in the same direction as in the full analysis.

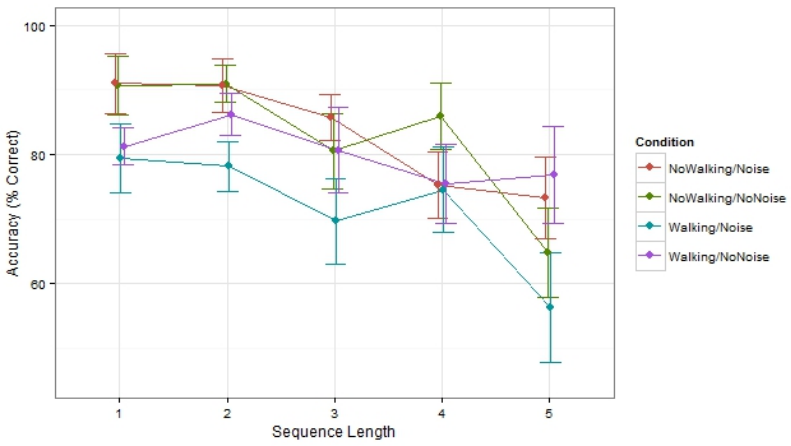

FIGURE 3: Location Coding- Percentage correct as a function of sequence length per condition. This graph shows the same results as Figure 4.6 in the results section. The only difference is that errorbars are displayed as well

Split-up Analysis Location Coding

Just like for the temporal coding, the performance of the location coding was examined at both extremes (sequence length 1 and 2 vs. 3-5).

Sequence Length 1-2

A 2(motion)*2(noise)*2(sequence length 1 and 2) repeated measures ANOVA showed a significant main effect for motion [$F(1) = 9.53$, $p = .009$, $\eta_p^2 = .42$]. The significant main effects for sequence length and the interaction effects for motion*noise and motion*noise*sequence length disappeared when only looking at sequence length 1 and 2. The main effect for noise still did not approach significance neither did the other interactions. The significant effects were in the same direction as in the full analysis above.

Sequence Length 3-5

A 2(motion)*2(noise)*3(sequence length 3, 4, 5) repeated measures ANOVA showed a significant main effect for sequence length [$F(4) = 6.93$, $p = .004$, $\eta_p^2 = .35$], as well as significant interaction effect for motion*noise [$F(1) = 6.45$, $p = .025$, $\eta_p^2 = .33$] and motion*noise*sequence length [$F(2) = 7.76$, $p = .002$, $\eta_p^2 = .37$]. The significant main effect for motion disappeared when only examining recall accuracy for sequence 3, 4 and 5. Neither noise nor the other interactions approached significance. The significant effects were in the same direction as in the full analysis.

Appendix F

Questionnaire Range IT

In te vullen door de testleider.

Nummer deelnemer: _____

Datum : _____

In te vullen door de testleider

Geslacht man/ vrouw*

Leeftijd …… jaar

P of T onderwijs

Na afloop van elke conditie vraagt de testleider de pp een cijfer tussen 0- 21 (heel laag – heel hoog) voor de mentale inspanning van deze conditie te geven

- Cijfer mentale inspanning conditie lopend:
- Cijfer mentale inspanning conditie staand:
- Cijfer mentale inspanning conditie lopend met lawaai:
- Cijfer mentale inspanning conditie staand met lawaai :

Debriefing na afloop van alle condities

Graag wil ik je verzoeken de volgende vragen zo eerlijk mogelijk te beantwoorden.
(Testleider leest vragen voor)

		Helemaal mee oneens	Mee oneens	Noch eens noch oneens	Mee eens	Helemaal mee eens
1	Ik vond het gemakkelijk om de afstandscategorieën van elkaar te onderscheiden	1	2	3	4	5
2	Ik vond het gemakkelijk om de verschillende tactoren van elkaar te onderscheiden	1	2	3	4	5
3	Ik begreep de betekenis van de trillers intuïtief	1	2	3	4	5
4	Ik vond het gevoel van een trilling comfortabel	1	2	3	4	5
5	Ik vond het gevoel van veel opeenvolgende trillingen comfortabel, ook over een langere periode	1	2	3	4	5

		Heel veel	Veel	Noch veel noch weinig	Weinig	Heel weinig
6	Ik denk dat ik fouten heb gemaakt in de test	1	2	3	4	5

7. Vond je de pauze tussen opeenvolgende signalen toepasselijk? Hoezo? Hoezo niet?

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_____

8. Zou je graag tijdens het lopen willen weten of er objecten links en rechts van je zijn? Hoezo, of hoezo niet?

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9. Zou je liever alleen maar informatie over objecten in je directe looppad willen krijgen?

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10. Hoe veel objecten zou je graag maximaal gepresenteerd krijgen?

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11. Zou je in je dagelijks leven willen weten of er obstakels op 5m afstand zijn?

_____

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13. In welke situaties zou je graag een obstakel-detectiesysteem willen hebben?

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14. Zou je de tactiele riem als obstakel-detectiesysteem graag dagelijks willen gebruiken?

_____

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_____

15. Wat is je mening over de tactiele riem? Positief / Negatief

Hoezo:

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16. Heb je nog opmerkingen of zaken die je kwijt wilt aan ons?

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