Ref. Ares(2019)1340573 - 27/02/2019

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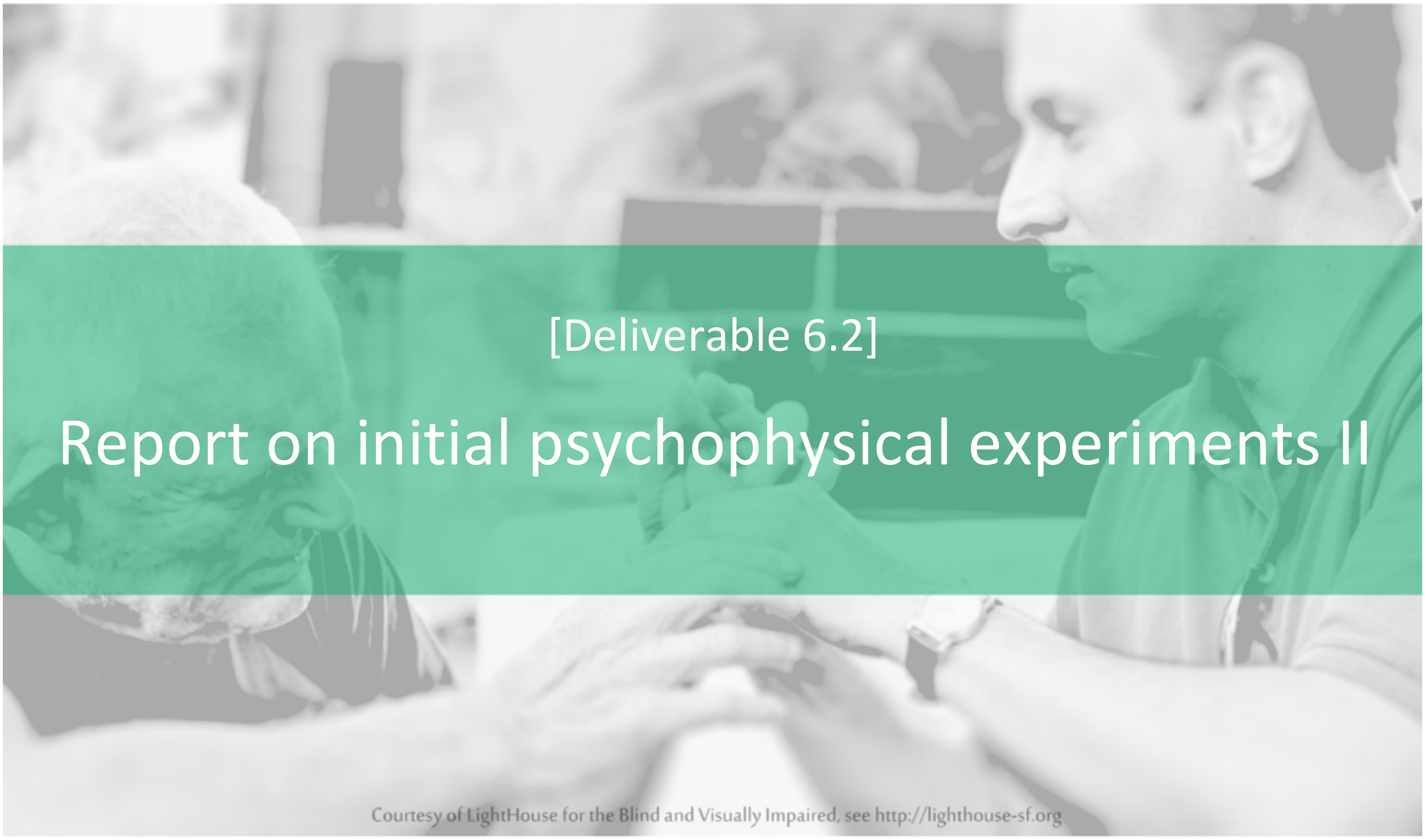

[Deliverable 6.2]

Report on initial psychophysical experiments II

Courtesy of LightHouse for the Blind and Visually Impaired, see http://lighthouse-sf.org

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 780814.

Dissemination level		
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Deliverable Details	
Deliverable number	6.2
Part of WP	6
Lead organisation	TU/e
Lead member	Astrid Kappers

Revision History			
V#	**Date**	**Description / Reason of change**	**Author / Org.**
v01	13-12-2018	Structure proposal	Plaisier/ TU/e
v02	13-02-2019	First draft for internal review	Kappers/ TU/e
v03	20-02-2019	Second draft addressing review comments submitted to HB	Kappers/ TU/e
v04		Final draft after PC's comments	
v05		Final draft submitted to the EU	

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Glossary	
Abbr./ Acronym	Meaning

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Executive Summary

WP6 focuses on identifying the information needed for exemplar tasks such as navigation and numerosity estimation, and proposing and testing haptic signals to convey this. These serve as input for a larger scale psychophysical study on how well various stimulations can be discriminated by sighted and hearing human participants and what would be the best location for stimulation. We focussed on both vibratory and thermal stimulation. As we had to wait for working prototypes developed in the other workpackages, we started with an extensive literature review of thermal stimulation focussed on body regions other than hand or face. This provides the required background knowledge for thermal testing and prototyping within this project. In addition, we did the first pilot experiments with vibrotactile stimulation. Focus here was on providing distance, direction and numerosity information to participants. As the pilot studies were quite promising, the next steps are to obtain approval from the respective ethics boards (Leeds and Eindhoven) for full scale psychophysical experiments that will be publishable in scientific journals and that will convey important insights for the further development of prototypes.

Literature overview of thermal perception

Background

The majority of studies on thermal perception and thermal devices have made use of stimulation on the hand. This needs not be surprising as hands are easily accessible and flexible in reaching a stimulus. Moreover, hands and fingers are more sensitive to thermal stimulation than most other body regions, although lips, cheek and forehead are even more sensitive (Stevens & Choo, 1998). However, if a thermal device is meant to be used as, for example, a feedback, alerting or communication system, as is envisioned in the current project, it might be desirable to apply the stimulation on other body parts in order to keep the hands free for other tasks. In the special case of devices designed for use in daily life by individuals with impaired vision and/or hearing, it is also undesirable to apply stimulation to the face as this would involve some clearly visible apparatus connected to the head.

In order to make good choices for types of stimulation (e.g., warming, cooling, rate of change of temperature), body regions to be stimulated and number of stimulators, it is of eminent importance to have a good knowledge of human thermal perception and to have a good overview of what has already been tested and published in the literature. The study presented in Annex 1 consists of an extensive overview of studies on thermal perception on other body parts than the hands or the face. The studies included range from rigorous psychophysics to rather informal pilot studies of thermal devices.

Insights

Perception

An important fact to take into account is that thermal sensitivity varies widely over the body, with mouth, face and fingers very sensitive, while foot and leg have poor sensitivity (Stevens & Choo, 1998). Moreover, the same stimulus presented to different body parts will be perceived as different in intensity (Stevens, Marks & Simonson, 1974). Humans are more sensitive to cooling stimuli than to warming stimuli, but if asked for preferences in, for example, communication, they prefer the warm stimulation.

A stronger thermal sensation can be obtained by either increasing the area of stimulation or increasing the intensity of the stimulation (Jones, 2009). As the intensity of the stimulation is summated over the area (i.e. thermal summation), spatial resolution of thermal stimulation is quite poor.

When using thermal stimulation in an application or experiment, it is essential to take all following factors into account, as all of these will influence the results: rate of temperature change, size of stimulated area, and body location. One should also be aware of possible influences of thermal illusionary effects, such as *thermal referral* (e.g. Watanabe, 2014), where thermal stimulation at one location influences the perception at another location, and the *thermal grill* (e.g. Craig & Bushnell, 1994), where a grid of warm and cold stimulations might create a painful sensation.

Thermal applications

As became clear from the overview, the number of thermal devices meant for stimulation on other body parts than hands or face is rather limited. Moreover, the studies that have been performed with these devices are usually quite informal. Most of these studies focussed on communication over a distance and just two investigated use of thermal stimulation as feedback mechanism in a computer game.

Overall people seemed to like the thermal stimulation over the (short) period of testing. In communication, warm had positive associations, whereas cold was interpreted as negative. In gaming, performance with thermal feedback improved.

Conclusions

Clearly, our knowledge of the potential use of thermal stimulation on other body parts than hands or face is severely limited. The question is why this is the case. Is this due to technical limitations, lack of interest by researchers, disappointing pilot results or simply because this research field is rather new? We do not know the answer to this question, but fact is in any case that the research field is new. Therefore, we conclude that there is certainly room for further exploration and more rigorous experiments.

From what we found, it is clear that we should not focus on conveying complex messages with thermal stimulation. Human thermal resolution is rather poor and thermal summation and thermal referral will complicate and thus limit the information that can be transmitted within a given time.

One idea that might be investigated further is the potential of signaling presence by means of thermal stimulation. From informal conversations with caretakers of persons with deafblindness we learned that uncertainty about the presence of a caretaker or time to arrival of a caretaker is an important issue for our target population. As some of the studies on thermal communication (e.g., Fujita & Nishimoto, 2004; Lee & Lim, 2012; Lee & Schiphorst, 2016) showed positive effects of thermal messaging, it might be worthwhile to investigate the potential of such an application.

Vibratory experiments - Numerosity

Background

In Workpackage 6, it is our task to find ways to communicate information to the user effectively using a haptic interface and to the use the prototypes developed in Workpackage 5 to validate this with psychophysical experiments. TU/e has been conducting interviews with people with deafblindness in the Netherlands for Workpackage 2. From these interviews it became clear that people with deafblindness would like to have access to information like how many people are in the room, who just entered the room or who is sitting next to me. Also, if people have a caregiver, they would like to know how far away their caregiver is. These are all types of information that could be displayed numerically. For distances and numbers this is obvious. In case of identifying a person, a certain person could be labeled with a certain number. Another example of information that can be numerically represented is time. What time of day is it? Or how long do I still have to wait?

One of the interviewees indicated that he/she uses an app (timebuzz) that tells the time by means of a series of vibration pulses on a smart watch and finds that very useful. A series of vibration pulses is a means of communication that is technically easy to achieve and at low cost. The disadvantage is that it can be time consuming to communicate information via a sequence of vibration pulses. If the vibration pulses are send too fast it becomes impossible to interpret the sequence. Also, concentration needs to be high the whole time that the sequence is displayed resulting in a high cognitive load. In this deliverable, we have started a series of psychophysical experiments to determine how a pulse sequence should be structured to minimise display time and cognitive load.

Numerosity judgment

From previous psychophysical studies it is known that numerosity judgment can be fast and accurate depending on whether the numerosity is small (<4) or large. This is the case in vision (Atkinson, Campbell & Francis, 1976; Trick & Pylyshyn, 1993), audition (Ten Hoopen & Vos, 1979; Camos & Tillmann, 2008) and touch (Riggs et al., 2006; Plaisier, Bergmann Tiest & Kappers, 2009). While in vision and touch numerosities are usually displayed simultaneously (e.g. a field of dots or grasping a number of spheres in the hand), they are often displayed sequentially in audition (i.e. a sequence of tones). In all three of these modalities evidence has been found that grouping of information can make numerosity judgment faster and more accurate (Mandler & Shebo, 1982; Plaisier, Bergmann Tiest & Kappers, 2010; Ten Hoopen & Vos, 1979). In other words: it makes the task easier.

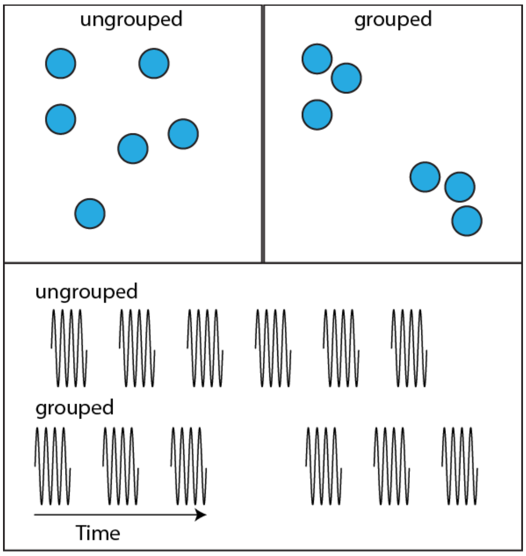

Figure 1 The top two panels show an example from visual perception. It is much easier to see that there are six dots in the grouped panel than in the ungrouped panel. Here we performed a pilot study as illustrated in the bottom part of the figure. We presented participants with a sequence of vibration pulses and tested whether grouping the pulses temporarily facilitated numerosity perception.

Most previous studies on haptic numerosity perception have displayed all items simultaneously. One study has investigated numerosity perception in touch with a sequence of vibration pulses (Iida, Kuroki, & Watanabe, 2016). In this study, it was found that numerosity judgment of a sequence of vibration pulses could be done, but that performance deteriorates with the time between pulses. They also found evidence that depending on the task, performance can be better when the pulses are distributed over the fingers of the two different hands instead of all delivered to fingers of the same hand.

Numerosity judgment and Deafblindness

To the best of our knowledge no studies have explicitly addressed numerosity perception in individuals with deafblindness. There has been, however, one study that investigated haptic numerosity judgment in congenitally blind individuals (Ferrand, Riggs, & Castronovo, 2010). In that study it was found that performance in congenitally blind individuals was largely the same as for blindfolded sighted individuals. This indicates that the cognitive processes on which haptic numerosity judgment relies are not mediated by vision. It also means that our findings can be used to optimise haptic communication for individuals with blindness or deafblindness.

Psychophysical pilot study

Overall, communication of numerosity information via vibration pulse sequences seems promising. In this project, we have started a series of experiments to determine how the pattern of the vibration pulses can be optimised for displaying numerosity information. The first experiment will focus on the effect of temporal grouping of the vibration pulses on performance of judging the number of pulses. We have completed the necessary pilot experiment to be able to start the full experiment. The results of the pilot experiment are presented in Annex 2. From these preliminary data it is clear that temporally grouping the vibration pulses can facilitate numerosity judgment considerably.

The prototype developed in Workpackage 5 was used to carry out the experiment. The aim of this pilot experiment was to test whether the experiment was doable for the participants, that the timing of the pulses was chosen correctly and to determine the number of participants necessary for the final experiment. This has to be established before an application for ethical approval can be made. The pilot results look promising, as the results are consistent across the pilot sample of 5 participants. We will apply for ethical approval shortly. Based on the pilot results and existing literature we will include 10 to 12 naive participants in the experiment. The design of the final experiment will be largely the same as the design of the pilot study.

Output

The results of this final experiment will be submitted as a Work in Progress paper to the World Haptics Conference 2019 in Tokyo. This study will be extended with one or two further experiments and submitted to a peer-reviewed journal such as IEEE Transactions on Haptics.

Vibratory experiments - Direction and distance

In order to locate a person or item relative to oneself, it is useful to have information not just as a number, but potentially as a co-ordinate to denote in which direction and how far away a given point of interest is. The purpose of this experiment was to explore the presentation of radial co-ordinates – taking the form of a direction and a distance – using a single vibration motor. Many studies have been conducted to look at the provision of navigational information through haptic means. Several studies use belts with vibration motors positioned at points about the waist, such that which motor is vibrating denotes the point of interest, such as the position of a person who is speaking (McDaniel et al., 2008) or the direction of magnetic North (Kärcher et al., 2012). The use of a pair of vibration motors on the left and right sides of the body to give turning instructions have also been explored for the purposes of supporting people who are deafblind in horseriding therapy (Ogrinc et al., 2018) and general navigation for people who are visually impaired (Dim & Ren, 2017). Similarly, the haptic presentation of distance information has been explored – using duration of vibration (McDaniel et al, 2008), vibration patterns (Gallo et al., 2010) or even devices that change shape (Spiers et al., 2018). Our interest in whether a vibration motor could be used to relay radial co-ordinates, lay in the potential for such signals to be delivered through simple devices, such as a single wristband, a mobile phone, or a single sleeve of a larger garment, leaving other parts free to convey other information.

Psychophysical pilot study

A vibrotactile pattern for delivering radial co-ordinates through a 1-second signal from a single vibration motor was designed such that distance was denoted by the intensity of the signal (a higher intensity denoting a closer point), and direction was denoted by the position of a brief (100ms) gap within a 1 second vibration signal. To assess whether this coding pattern was worth pursuing further, a short pilot study was carried out. Details of the experiment and results can be found in Annex 3.

The study involved three members of the research team, and tested the direction signal alone and then together with varying intensities to represent distance, again using the prototype developed in Workpackage 5. The results were encouraging, despite the novelty of the signal: errors were generally within one increment of the correct answer. Participants were best at recognising the extreme directions, and the centre, though performance decreased when the distance and direction signals were combined. Nevertheless, this was sufficiently encouraging to warrant further study, with consideration given to the need for practice and training, and for learning effects. Accordingly, application for ethics approval to conduct a study with naïve participants and a greater number of trials has been made.

Summary and Next Steps

This pilot study has examined the use of a single vibration motor for delivering radial co-ordinates and directions. This will be followed up by a full study with naïve participants, and if it continues to prove promising then the next step will be to begin testing the ability to guide a participant to a target point in real time, assessing the ability of these signals to be interpreted when not in a laboratory environment, over the summer of 2019. These combined experiments will be written up and submitted to the IEEE Transactions on Haptics.

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Thermal Perception and Thermal Devices used on Body Parts other than Hand or Face

Astrid M.L. Kappers and Myrthe A. Plaisier

Abstract—Most fundamental research on thermal perception focusses on the fingers or the hand. Also most existing and proposed thermal devices are meant to be applied to hand or fingers. However, if the hands are needed for other tasks, application of thermal stimulation to other body regions should be considered. This paper surveys the literature on thermal perception and thermal devices relevant to such other body regions. It starts with a short description of the experimental methods used in the various studies. This is followed by thermal psychophysical studies on detection, adaptation, spatial summation and resolution. Next some thermal illusions are presented, and the few studies on thermal communication and applications are summarized. Finally, this survey ends with some conclusions.

Index Terms—Overview, thermal stimulation, psychophysics, devices, body

◆

1 INTRODUCTION

THE majority of studies on thermal perception and thermal devices have made use of stimulation on the hand, (e.g., [1]). This needs not be surprising as hands are easily accessible and flexible in reaching a stimulus. Moreover hands and fingers are more sensitive to thermal stimulation than most other body regions, although lips, cheek and forehead are even more sensitive [2]. However, if a thermal device is meant to be used as, for example, a feedback, alerting or communication system, it might be desirable to apply the stimulation on other body parts in order to keep the hands free for other tasks. In the special case of devices designed for use in daily life by individuals with impaired vision, it is also undesirable to apply stimulation to the face as this would involve some clearly visible apparatus connected to the head. The goal of the present paper is to give an extensive overview of studies on thermal perception on other body parts than the hands or the face. The studies included in this overview range from rigorous psychophysics to rather informal pilot studies of thermal devices.

When comparing the results of various studies, many issues have to be taken into account. Age and gender of different populations of participants may directly influence the results [2]. In the present case of thermal stimulation, the physical parameters of the stimulus such as contact size, rate of change of temperature, and baseline temperature are all important and may have huge influences on the results. Also the body region stimulated is of major importance, as [2] showed a 100-fold sensitivity variation over the human body surface. Finally, there are many different experimental methods to assess psychophysical performance of individuals, but it is very important to realize that different methods will lead to different outcomes; a threshold measured via a two-alternative forced choice method will not necessarily be the same as a threshold obtained via the method of limits (see below for an explanation of these methods).

The studies discussed in this overview are all published in peer-reviewed scientific journals or conference proceedings, so this excludes devices that might be on the market without being published. All references of the included papers are checked for further relevant studies. In addition, papers that cite the included studies have also been checked for relevance. In several of the studies described below also thermal stimulation on hands or face has been studied in addition to other body regions, but these results will be omitted from this overview.

As it is important to have some basic understanding about the psychophysical methodology used in the various studies, this overview will start with a brief introduction of relevant terms and methods. Next, studies on thermal detection, adaptation, summation and resolution will be presented. As thermal perception is also susceptible to illusions, a separate section is devoted to illusions. Finally, more applied research on thermal communication and other applications will be presented, followed by some conclusions.

2 METHODS AND TERMS USED IN THE STUDIES

Perceptual performance of humans is often expressed in terms of *thresholds*. A threshold indicates the amount or intensity of a stimulus needed for the stimulus to be consciously perceived. Often the threshold is more precisely a *difference threshold*, which is the minimum change in intensity needed to perceive the stimulus as different from a reference sitmulus. For thermal perception the threshold indicates the minimal difference in temperature (either heating or cooling) from a baseline temperature that is noticed by a participant. The threshold is also termed *just-noticeable difference* or *JND*.

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Manuscript received ??; revised ??.

Thresholds can be measured in different ways and the outcome will depend on the method. A method often used for thermal thresholds is the *method of limits (MoL)*. Starting from a baseline temperature (usually close to skin temperature), the temperature of the stimulus increases or decreases in small steps until the participant indicates that s/he noticed a change in temperature. Usually, this procedure is repeated several times and the average end temperature is defined as the threshold. In this way, separate *warm thresholds (WT)* and *cold thresholds (CT)* can be determined. In some studies, the stimulation reverses sign when a threshold is reached and stimulation continues to the opposite threshold. Thus, one goes back and forth between the WT and the CT. The average value of this difference is the so-called *difference limen (DL)*.

Another method to determine thresholds is the *two-alternative forced choice method (2AFC)*. In each trial, a participant is presented with two stimuli and s/he has to choose which of the pair contained the actual stimulation. This procedure is a more sensitive way to measure thresholds, but it is also much more time-consuming as many pairs have to be presented to the participants. A variation of this method is the *three-alternative forced choice (3AFC)* method, where the participant has to choose which of three intervals contained the stimulus. Such forced choice methods can be used either in combination with the *method of constant stimuli*, where all stimulus pairs or triples are presented an equal number of times, or with a *staircase procedure*. With this latter procedure, the difference between the stimuli of a pair is made smaller after one or more correct answers and made larger after one or more incorrect answers. After how many correct or incorrect answers the difficulty reverses determines the percentage correct to which this procedure converges. For example, a one-down/one-up staircase converges to a 77.85% correct threshold, whereas a four-down/one-up staircase converges to 85.84% [3].

The physical characteristics of the stimulus will influence the threshold. An important parameter for thermal experiments is the *rate of change* or *RoC*. A change in the temperature of stimulation cannot be instantaneous and the RoC indicates whether this change occurs slow or fast. If the RoC is very small, the change in temperature might go unnoticed, leading to increased thresholds (see next sections).

Another common psychophysical method which is also used in some of the studies discussed in this paper is *magnitude estimation*. In this method, the task of the participant is to rate the “magnitude” of the stimulation. This magnitude can be any property such as intensity, size, or duration. In most cases, the scale participants have to use for their rating is arbitrary, as long as they use the scale consistently over all stimuli: if a stimulus is perceived as having twice the magnitude of another stimulus, they should double their rating. Sometimes the extremes of the scale, for example 1 and 100, are fixed by the experimenter. There exist many variations of this method, all with their own advantages and disadvantages.

Finally, some of the studies make use of scoring on a *Likert scale*. Participants have to score a property in more psychological terms like dislike–like, not comfortable–very comfartable, etc. Such scales are typically used in questionnaires after an experiment.

There are many books and papers that explain the above-mentioned terms and methods in much more detail. A quite random selection can be found here: [4], [5], [6], [7], [8].

3 PSYCHOPHYSICS

3.1 Thermal Detection - Basic Psychophysics

There are quite a number of studies that investigated how well participants can detect a change in temperature (see Table 1). Thermal detection thresholds are the smallest difference in temperature that can be detected when the skin warms or cools starting from a certain baseline temperature. The detection thresholds will somewhat depend on the method used to determine these thresholds.

In [9] the skin of the dorsal forearm was first adapted to a temperature of 31.5°C. Using the method of limits (MoL) they determined both warm and cold thresholds (WT and CT) for different rates of temperature change (RoC). The warm thresholds were about 0.4°C if the RoC was 0.1°C/s or higher. Lower RoCs led to substantial increases of the threshold. The cold thresholds were about 0.2°C if the RoC was 0.1°C/s or higher and thus somewhat smaller than the warm thresholds. The same group also showed that warm thresholds measured with either radiant stimuli or with contact stimuli are similar [21]. Also [10] measured warm and cold thresholds, for both adults and children. They used a 2AFC staircase method in which pairs consisting of one stimulus with a stable temperature and one stimulus with a warming or cooling stimulus were presented to participants, who had to decide which of the stimuli of a pair contained the changing temperature stimulus. Although thresholds could differ about an order of magnitude between participants, within participants the thresholds turned out to be quite stable. Age and gender did not influence the thresholds. Like in [9], they found somewhat smaller thresholds for cooling. Using a more sophisticated set-up to measure thresholds, [11] reports smaller thresholds than the earlier studies. Warm and cold thresholds measured on wrist, forearm or thigh hardly differed (about 0.23 and 0.15°C, respectively), but warm thresholds measured on the ankle were substantially larger (1.35°C). The influence of much higher RoCs (1.4, 2.4, and 3.9°C/s) on the warm and cold thresholds on forearm, leg, cheek and hand was investigated in [12]. For all tested skin regions, they found an increase of the warm threshold with increasing RoC, while the cold thresholds remained the same. Although this seems to be in contradiction with the results presented in [9], it should be noted that the RoCs used lie in quite a different range. [13] showed that the legs are most sensitive to thermal stimulation with an RoC between 2.5 and 2.8°C/s.

The major aim of [14] was to compare warm and cold thresholds to difference limen (DL) thresholds. The latter thresholds are determined by alternating warm and cold stimulation; when a participant notices a temperature change, the temperature change is reversed. Thus, one of the questions was whether the DL threshold is equal to the sum of the warm and cold thresholds. As WTs and CTs turned out to be much less variable than DL thresholds, they advocate a strong preference for separate measurements of WTs and CTs. The same group measured WTs and CTs on

TABLE 1
Thermal detection - basic psychophysics.

Reference	Location	Participants	Stimuli	Task	Outcome
Kenshalo et al. [9]	arm dorsal site near elbow	19–27 (3)	31.5°C - cooling, warming: 0.3, 0.1, 0.05, 0.02, 0.01°C/s	3AFC MoL	- WT, CT constant above 0.1°C/s - rapid increase below 0.1°C/s
Gray et al. [10]	volar forearm	19–55 (13) 7–9 (11)	3.6 cm^2	2AFC detection staircase	- median threshold: - warming +1.04°C - cooling -0.15°C - no influence of age or sex - substantial differences between participants - high test-retest correlation
Jamal et al. [11]	wrist, forearm, thigh, ankle	6–73 (106)	34-35°C 1°C/s - warming - cooling	2AFC detection	thresholds WT/CT: - wrist: 0.23°C / 0.15°C - forearm: 0.24°C / 0.15°C - thigh: 0.23°C / 0.15°C - ankle: 1.35°C / 0.17°C
Pertovaara & Kojo [12]	distal forearm, leg	20-40 (2f, 6m)	- cooling, warming: 1.4, 2.4, 3.9°C/s	detect: - warm, heat, pain, cool	- influence of RoC the same for all body sites - warm, heat, pain thresholds increase with RoC - CT independent of RoC
Claus et al. [13]	- wrist, ankle - leg	19-78 (77) 16-65 (32)	2.5×5 cm^2 35°C - warming: 0.9-4.2°C/s - cooling: 1.1-2.8°C/s	detect	- most sensitive: legs with 2.5-2.8°C/s - CT lower than WT
Hilz et al. [14]	forearm 4 cm from wrist volar site	18–56 (20)	30°C, 35°C - warming, cooling	MoL: - WT - CT - DL	- WT: 1.6-2.3°C - CT: 1.6-2.2°C - DL: 3.9-4.6°C
Hilz et al. [15]	foot, calf, forearm	3–7 (74)	32°C - warming, cooling: 1°C/s - 1.5×2.5 or 2.5×5 cm^2	MoL: - WT, - CT	- no difference between age groups - foot: WT 2.9°C, CT 3.5°C - calf: WT 3.1°C, CT 3.7°C - forearm: WT 2.5°C, CT 2.6°C - larger probe → lower threshold
Hilz et al. [16]	foot, calf, forearm	7–18 (225)	32°C - warming, cooling: 1°C/s - 1.5×2.5 or 2.5×5 cm^2	MoL: - WT - CT	- larger probe → lower threshold - MoL suitable for quick evaluation of thermal sensitivity
Hilz et al. [17]	foot, calf, forearm	18–80 (225)	32°C - warming, cooling: 1°C/s - 1.5×2.5 or 2.5×5 cm^2	MoL: - WT, - CT	- larger probe → lower threshold - MoL suitable for quick evaluation of thermal sensitivity
Madera et al. [18]	forearm	20–29 (2f, 5m)	radiant stimuli warming: 0.033, 0.01, 0.2°C/s	MoL: - WT	- larger RoC gives higher detection rate - larger RoC gives shorter detection time
Stevens & Choo [2]	13 body regions	18-28 (20) 40-60 (20) $\geq$ 65 (20)	33°C 3 s - cooling: 1.9°C/s - warming: 2.1°C/s	staircase 2AFC stimulus presence	- sensitivity varies 100-fold over body: - leg/foot relatively poor - sensitivity cold > warmth - sensitivity declines with age - sensitivity for warm and cold correlates
Lee et al. [19]	12 body sites	∼21(20m)	- warming, cooling: 0.1°C/s	MoL	- tendency for different thresholds for tropical and temperate natives
Heldestad Lillieskӧld & North [20]	foot, leg, thigh, forearm, upper arm	16–72 (75)	32°C 1°C/s - warming, - cooling	MoL: - WT - CT	- thresholds depend on body site - thresholds higher in lower parts of body - WT > CT

For participants first the age or age range is given in years and between brackets the number of participants (f indicates females, m males). 2(3)AFC stands for two (three) alternative forced choice. MoL is method of limits. WT is warm threshold, CT is cold threshold. DL is difference limen. RoC is rate of change.

forearm, foot and calf for large groups of children, juveniles and adults in order to obtain normative data for comparison with patients (in particular, patients with neuropathy) [15], [16], [17]. They found no difference between the thresholds of age groups 3–4-, 4–5-, 5–6- and 6–7-years, nor between boys and girls [15]. A larger area of stimulation yielded lower thresholds [15], [16], [17]. The main conclusions from this series of studies are that the method of limits is well suitable for a quick determination of the thresholds, that there is sufficient intertrial reproducibility, that a larger probe is preferred if possible (i.e. can be placed flat on the skin) and that it is not necessary to pre-warm the skin before testing. A recent study [18] showed that also for radiant stimuli, a larger RoC leads to a higher detection rate and shorter detection times.

An extensive investigation of the influence of both age (between 18 and 88 years) and body region (13 regions, among which lower and upper arms, belly, back, thigh and calf) on the warm and cold thresholds was presented in [2]. For all ages, an enormous influence of body region was found: the face was about 100 times more sensitive than the foot. Cold thresholds were everywhere lower than warm thresholds. There was a strong correlation between the WTs and CTs of participants. Finally, the study also showed a decline of thermal sensitivity with age, with the most prominent declines in the extremities.

In [19] it was investigated whether natives from different climate zones (tropical versus temperate) had different warm and cold thresholds. Using the method of limits, they tested 12 body regions of 10 Japanse individuals (temperate zone) and 10 Malaysians (tropical zone). All experimental tests took place at the same location in Japan, so conditions could be kept the same for all participants. Consistent with previous studies, thresholds widely depended on body region, with the calf the less sensitive. They further reported a tendency that the individuals from the tropical zone have a somewhat lower sensitivity to detect warmth.

In a very recent study, the warm and cold thresholds of a large group of 75 participants ranging in age from 16 to 72 years were measured using the method of limits at 8 body regions [20]. Their results were consistent with the earlier studies: WTs were generally higher than CTs at all body regions, and the thresholds of the lower parts of the body were higher than those of the upper parts.

3.2 Thermal Detection - Applied

A few studies investigated thermal detection with body parts other than the hand or face in a more applied setting (see Table 2). [22] studied thermal detection at body sites where potentially a mobile device could be carried, like the fingers, the thenar, the forearm and the upper arm. They found that the intensity of the stimulus, that is the rise or fall of temperature with respect to baseline, influences detection: higher intensities result in better detection and faster response times. Cooling is detected faster than warming. A higher rate of change improves detection, but reduces comfort. Thresholds for the different body sites were as follows: thenar (1.9°C), forearm (2.2°C), upper arm (2.3°C) and finger (2.9°C). Similar tests in an indoor mobile setting (as opposed to a static situation) showed that performance dropped significantly, although most of the observed patterns and dependencies remained. The same group also investigated the influence of placing a textile between the skin and the thermal stimulus [23]. They placed the stimulus either directly on the skin or on a piece of cotton or nylon on the thenar, the thigh or the waist. Also in these experiments, higher intensity and faster rate of change improved performance. Detection percentage depended strongly on material, namely 65%, 47%, and 36% for none, nylon and cotton, respectively. This indicates that materials with lower thermal conductivity require a higher intensity. However, users rated comfort higher when the stimulation was provided via a textile.

Experiments with a quite different focus were done in [24] who tested a device worn around the wrist capable of gracefully interupting attention of the user. They found, similar to the previously mentioned studies, that intensity and rate of change both influence detection and that cooling has a stronger effect than warming. In [25], the authors focused on the usefulness of thermal stimulation in tropical circumstances. In the tropics, ambient temperatures might change suddenly, for example, when moving from inside an airconditioned building to outside. They reported that both ambient temperature and ambient humidity have a significant influence on detection of a thermal stimulus, with higher detection rates for higher temperatures, and lower detection rates for humidity above 60%. Although they also conclude that sudden change of ambient environment has no influence on detection, it is not clear on which data that conclusion is based. From subjective comfort ratings it followed that participants preferred the cooling stimulus. In [26], the same group tested whether thermal feedback would be suitable in a noisy or a bumpy environment. The noisy environment was created by exposing the participants to 120 decibel noise from a concert; in the bumpy environment condition, participant had to stand on a pivotal vibration plate machine with 30 hertz vibration. They compared the detection rates of two types of auditory stimulation, vibratory stimulation and thermal stimulation in noisy or bumpy environments. The stimuli could be presented either in isolation or in various combinations. In both environments, performance was significantly better with thermal stimulation than with the other three types. Performance further improved with multisensory stimulation.

3.3 Thermal Adaptation

Only one study [27] investigated thermal adaptation at a body site other than the hands (see Table 3). The focus of this study lies on introducing a better method to measure adaptation and to investigate the time course of adaptation in more detail. At the start of the experiment, participants first had to sit for 20 minutes in an airconditioned room. After this period, the temperature of their dorsal forearm was measured. Subsequently, a Peltier element with the same temperature as the skin was placed on the dorsal side of the forearm. The task of the participant was to adjust the temperature of the element such that its temperature was just detected as warm or cold (in different trials). Every five minutes, the experimenter changed the temperature of the element back to neutral. Over a period of 40 minutes,

TABLE 2
Thermal detection - applied.

Reference	Location	Participants	Stimuli	Task	Outcome

Wilson et al. [22]	- forearm, upper arm
	- palm, forearm, upper arm
		21-57 (14)
		23-41 (14)
			duration: 10 s
			intensities: 1, 3, 6°C
			- warming, cooling: 1, 3°C/s
				- detect
				- rate:
				  - intensity
				  - comfort
				- conditions:
				  - static
				  - mobile
					- intensity influences detection: 53%, 91% and 97%
					- cooling detection faster than warming
					- thresholds: forearm (2.2°C), upper arm (2.3°C)
					- response time decreases with intensity
					- RoC influences detection
					- comfort decreased with RoC
					- static better than mobile

Halvey et al. [23]	thigh, waist	22–39 (15)	duration: 10 s
			intensities: 1, 3, 6°C
			- warming, cooling: 1, 3°C/s
			interface: none, nylon, cotton
				- detect
				- rate:
				  - intensity
				  - comfort
					- intensity influences detection: 19% (1°C), 58% (3°C) and 71% (6°C)
					- interface influences detection: 65% (none), 47% (nylon), 36% (cotton)
					- RoC influences detection
					- no detection difference between warming, cooling
					- detection faster with cooling
					- detection slower with thigh
					- comfort decreased with intensity

Bolton et al. [24]	wrist	(15)	10 s intensities: 0.5, 1, 1.5°C - warming, cooling: slow, high, medium	detection	- intensity influences detection - RoC influences detection - cooling better than warming
Janjeng & Leelanupab [25]	wrist	24	intensities: 3, 6°C - warming, cooling: 1, 3°C/s different ambient temperatures	detection rate: - comfort - intensity	- faster detection with RoC 3°C/s - preference for cold stimuli - significant influence of ambient humidity - significant influence of ambient temperature - no influence of sudden change of ambient temperature
Ketna & Leelanupab [26]	wrist	21–30 (12f, 12m)	cooling: 10 s, 3°C/s	detection in noisy or vibratory environment	- detection rate higher with thermal stimuli

For participants first the age or age range is given in years and between brackets the number of participants (f indicates females, m males). RoC is rate of change.

the temperature difference needed to detect the temperature of the element as warm or cold increased from just a part of a degree to about 4°C, clearly indicating adaptation. This temperature range was much smaller than reported by other studies. The authors attribute this difference to the better control of their stimulus and experimental conditions, and size and location of the stimulated area (hand versus forearm). They also showed that adaptation above skin temperature occurs more rapidly than below skin temperature.

3.4 Thermal Spatial Summation

A stronger thermal sensation can be obtained by either increasing the *area* of stimulation or increasing the *intensity* of the stimulation [33] (see also Table 4). As the intensity of the stimulation is summated over the area (i.e. thermal summation), spatial resolution of thermal stimulation is quite poor. In [28] and [29] the spatial summation of warmth was studied on the back. With a magnitude estimation task, they showed that for a given area of stimulation, the perceived warmth increased as a power function of intensity. The exponent of the power function was smaller for larger areas. The power functions for the various areas converged near the level of painful stimulation. This research was extended to include also forearm, upper arm, shoulder, chest and calf as investigated body regions in [30] with basically the same results: strong spatial summation of intensity over area. In [21] it was shown that different methods of stimulation, namely radiant stimuli or contact stimuli, lead to similar results. They also showed that at threshold, the product of area and intensity is constant, indicating that a larger area can compensate a lower intensity, and vice versa.

An important difference between the various body regions was that the same stimulus caused quite different magnitude estimates, indicating that the stimulus warmth was perceived differently depending on body region, especially for relatively weak stimulation [30]. For an equal magnitude estimate, the intensity of the stimulation needed on the forehead was smallest and for the calf highest, with cheek, chest, abdomen, shoulder, back, forearm, upper arm and thigh in increasing order in between. The same group also showed strong spatial summation for cooling stimuli [31] on both the back and the forearm. However, in contrast to the convergence found for higher levels of stimulation with warm stimuli by [28] and [29], no such convergence was found for cooling stimuli. This means that for cold stimulation near the pain threshold, the relative contributions of size and intensity remained the same.

In [32] it was investigated whether thermal spatial sum-

TABLE 3
Thermal adaptation.

Reference	Location	Participants	Stimuli	Task	Outcome
Kenshalo & Scott [27]	forearm	(2f, 2m)	14.4 cm^2 0.3°C/s 11.8 g/cm^2	adjust just detectable warm or cold	- complete adaptation after 25 minutes - rapid adaptation for temperatures close to skin temperature - adaptation above skin temperature more rapid than below skin temperature

The number of participants is given between brackets (f indicates females, m males).

TABLE 4
Thermal spatial summation.

Reference	Location	Participants	Stimuli	Task	Outcome
Marks [28], Stevens & Marks [29]	back	(14m)	3 s 31 – 324 cm^2, 36 – 282 mW/cm^2	magnitude estimation	- subjective warmth grows with area and intensity - rate of growth depends on area - convergence near pain threshold
Stevens et al. [30]	forearm, calf, back, shoulder, chest, abdomen, upper arm	(18m/2m)	- 5 sizes - 6 intensities	magnitude estimation	- subjective warmth grows with intensity - rate of growth depends on area - forearm and calf less sensitive than forehead - perceived intensity depends on location
Kenshalo et al. [21]	forearm, back	(1f, 1m)	3 s radiant stimuli: 1, 2, 3, 4, 6, 8, 12 cm^2 contact stimuli: 1.7, 7.1, 14.4 cm^2	MoL	- complete summation: A (area) x I (intensity) = constant - back least sensitive - radiant and contact stimuli give same results
Stevens & Marks [31]	forearm, back	(15)	2.0 – 19.6 cm^2 2 – 12°C RoC $>$ 1°C/s	magnitude estimation	- strong spatial summation - subjective cold depends on intensity and size of area - cold and warm summation follow different patterns
Rósza & Kenshalo [32]	forearms 19 cm from wrist	20–26 (3m)	18.4 mm^2 cooling 3 s RoC 1°C/s AT: 24, 28, 32, 36, 40°C 3 intensities unilateral/bilateral	report: -temperature change (yes/no) - confidence	spatial summation over the two arms: - both near threshold and suprathreshold - at all adaptation temperatures - at all intensities

For participants first the age or age range is given in years and between brackets the number of participants (m indicates males, f females). MoL is method of limits. WT is warm threshold, CT is cold threshold. RoC is rate of change. AT is adaptation temperature.

mation also occurs for non-adjacent areas of stimulation. By stimulating either one forearm or both forearms simultaneously, they could show that indeed spatial summation also takes places over the two arms. They tested this for 5 different adaptation temperatures and 3 different intensities (near threshold and suprathreshold) and in all conditions they found spatial summation. The authors conclude that their results indicate that spatial summation occurs in the central nervous system.

3.5 Thermal Resolution

For the design of thermal devices, it is of eminent importance to know how much thermal stimuli need to differ in order to be distinguishable (see Table 5). The study in [34] reports a recognition experiment in which participants had to recognize whether a thermal stimulus was 3 or 6°C below or above skin temperature, or just skin temperature. Of the total of 180 trials (15 trials for each of 12 participants) only 70 stimuli were identified correctly. However, there were huge differences among participants, with some participants apparently performing close to chance level. The main confusions were made between -3 and -6°C, and between 3 and 6°C, although also confusions between hot and cold stimuli occurred, causing 22% of the errors.

In [35] participants received radiant stimuli on their volar forearm, and they were asked whether the stimulation was closer to their wrist or to their elbow. For reference before each trial, the midline of their arm, halfway between wrist and elbow, was touched by the experimenter. Distance from the midline was either 2.5, 4, or 5.5 cm. Performance increased with distance and stimulus intensity. For the lowest intensity and shortest distance, performance was only just above chance level, but for the highest intensity and largest distance a performance level of 94% was achieved. For one participant, the authors compared this performance with a similar experiment in which light touch was used as stimulation. In this condition, almost 100% correct was reached, indicating far superior performance with tactile as compared to thermal stimulation.

In one experimental condition in [36], participants had to recognize the relative temperature of stimuli ranging from 29 to 35°C in steps of 1°C presented to a location in the center of their forearm. Performance was only 35% correct (chance level 14%). In another condition the same stimuli were presented simultaneously to three locations on the forearm. The authors termed this the amplification condition, as now three locations were always stimulated simultaneously and hence the total thermal intensity was increased. In this condition, performance increased somewhat to 49%. In a third condition, termed quantification condition, 0, 1, 2 or 3 locations were presented simultaneously with either the lowest or the highest temperature (so again 7 levels of intensity). The stimulus with the lowest temperature consisted of stimulation of 3 locations with the minimum temperature (29°C), and the warmest stimulus consisted of stimulation of 3 locations with the maximum temperature (35°C). Stimuli in between consisted of 1 or 2 stimulated areas with the warmest or coldest temperature, and one in which no stimulation was presented. Also in this condition, a similarly low performance (44%) was achieved. The latter two methods achieved significantly better performance than the single stimulus condition, which is probably caused by the larger differences in intensity between the 7 stimuli.

3.6 Illusory Thermal Patterns

As presented in Table 1, thermal thresholds depend on the rate of change of the stimulation: higher rates of change result in faster detection and thus lower detection thresholds. In three studies [37], [38], [39], the authors make use of this phenomenon in the creation of a stimulus that is perceived as continously cooling, whereas actually the average temperature remains constant (see Table 6). They term this asymmetric cooling. The forearm is stimulated with a small number of quickly cooling Peltier elements and a larger number of slowly heating elements. As the heating of the elements is so slow that it is below threshold, the heating is not perceived, resulting in the illusion of constant cooling. In [37] the authors investigate in detail the optimal arm locations, and cooling and heating cycles to induce this illusion. Of the three locations tested, stimulation of the dominant posterior forearm gave the strongest thermal sensation, as compared to the dominant and non-dominant anterior forearms. Time cycles (in s) of heating/cooling of 30/10 and 21/7 gave a stronger effect than 45/15. In [38] the authors investigate the opposite illusion (asymmetric heating), a stimulus that is perceived as constantly heating. Here, the cooling of the elements is so slow that is it below the perception threshold and thus only the heating stimulation is perceived. Both illusions were further investigated in [39]. Among their findings was a counterintuitive effect that asymmetric heating was perceived as cooling.

A well-known thermal illusion is the thermal grill illusion, first demonstrated by Thurnberg in 1896 and later investigated in more detail in [46]. Placing one's hand on a thermal "grill" consisting of interlaced warm and cool bars of temperatures that are all well within harmless levels of warm and cold illicits a burning and painful sensation. In a rather preliminary study [40], the authors describe their intention to use this illusion as the basis for a tactile language. They developed a Thermoelectric Tactile Display (TTD) consisting of three thermal elements. Interestingly, they report that already with only two thermal elements, one cold and one warm, participants experienced the thermal grill illusion. Unfortunately, they did not continue their research on this topic.

In [41] participants were presented with an array of 4×4 Peltier elements on their forearm. In the first phase of a trial, all elements had the same temperature within a range of 22.5–37.5°C. In the second phase, half of the elements increased in temperature, the other half decreased, keeping the average temperature, and thus also skin temperature constant. Cooling and warming was done in a checkerboard pattern. In the third phase, the temperatures of the elements remained at the level they had reached during the second phase. Participants were constantly required to report their thermal sensation by adjusting a dial ranging from "painful cold" via "neutral" to "painful hot". It was found that the checkerboard type of stimulation in phase 2 was perceived as warmer than the homogeneous stimulation in phase 1 for skin temperatures above 30°C, whereas for skin temperatures below 30°C the checkerboard pattern was perceived as cooler than that of the homogeneous temperature, even though the actual skin temperatures were the same. Although the author did not discuss his findings in terms of the "thermal grill" illusion, it might be that his findings could be thought of as a "thermal grid" illusion. In both cases, the perceived temperature of the stimulation is changed towards more extreme temperatures.

In [47] the phenomenon was shown that when the index and ring fingers were stimulated with either a warm or a cold stimulus, the temperature felt by the middle finger was the same, even though the actual temperature of the stimulus was neutral. The author termed this illusion "thermal referral". In [42] it was investigated how two thermal stimuli on the forearm, one near the wrist and one near the elbow, and either of a warm, cold or neutral temperature, would be perceived. As was expected on the basis of the thermal referral phenomenon, the perceived temperature at one location was influenced by the temperature of the other location, although this influence was asymmetrical: The temperature perceived near the elbow was influenced more by the temperature of the wrist stimulation than vice versa. Some participants even experienced a burning sensation at the elbow such as in the thermal grill illusion when the wrist was stimulated with a cold stimulus and the elbow with a warm stimulus, or vice versa. Thermal referral on two locations on the forearm was confirmed in [43]. In addition, these authors also tested simultaneous stimulation of three locations, yielding similar results. Moreover, if the center stimulus was different from the outer stimuli (hot versus cold or vice versa), the perception was often confusing ("paradoxical") and some participants perceived this as a painful sensation (like in the thermal grill illusion).

An interesting tactile illusion is the so-termed "cutaneous rabbit" [48]. When the forearm of a participant is stimulated with a series of brief pulses at three locations, for example five pulses near the wrist, then five halfway the forearm, followed by five near the elbow, the perception will be that of a series of more or less equally spaced pulses from wrist to elbow (hence the name cutaneous rabbit).

TABLE 5
Thermal resolution.

Reference	Location	Participants	Stimuli	Task	Outcome
Song et al. [34]	wrist	24–30 (8f, 4m)	-6, -3, 0, +3, +6°C with repect to baseline	identify	- RT not dependent on stimulus - many errors (110 of 180) - confusions: -3°C and -6°C and, +3°C and +6°C
Taus et al. [35]	forearm 6 sites	(3m)	68, 138, 224, 398 mW/cm^2 3 s	localize: distal or proximal	- 59% correct for lowest intensity, shortest distance - 94% correct for highest intensity, greatest distance
Tewell et al. [36]	forearm 3 sites	(2f, 10m)	7 stimuli - 29 – 35°C - 1, 2, 3 sites	identify on Likert scale	- single site: 35% correct - 3 sites: 49% correct - mixed sites: 44% correct

For participants first the age or age range is given in years and between brackets the number of participants (f indicates females, m males). RT is reaction time.

TABLE 6
Illusory Thermal Patterns.

Reference	Location	Participants	Stimuli	Task	Outcome
Manasrah et al. [37]	forearm (dom. ant., non-dom. ant., dom. pos.)	18–55 (21)	12 Peltier elements asymmetric cooling and heating 30/10, 21/7, 45/15 heating/cooling time cycles (s)	describe thermal sensation	- a feeling of decreasing temperature was elicited (without actual change in skin temperature) - strongest thermal sensation at dominant posterior forearm - 30/10 and 21/7 heating/cooling time cycles give stronger sensation than 45/15.
Manasrah et al. [38]	forearm	18–55 (10)	12 Peltier elements asymmetric cooling and heating	- cooling threshold - describe thermal sensation	- a feeling of increasing temperature was elicited (without actual change in skin temperature)
Hojatmadani & Reed [39]	forearm	18–34 (7f, 11m)	12 Peltier elements asymmetric cooling and heating	describe thermal sensation	- asymmetric heating created a cold perception - objects at skin temperature are perceived warmer
Oron-Gilad et al. [40]	forearm	(3)	warm/cold 3 Peltier elements 15×15 mm	- thresholds - thermal grill	- very informal pilot experiments - thermal grill illusion can be generated with only two "bars"
Young [41]	forearm	15–50 (5f)	16 Peltier elements cooling and heating in checkerboard pattern	report thermal sensation	- checkerboard pattern perceived warmer (colder) than homogeneous pattern for average skin temperatures above (below) 30°C
Watanabe et al. [42]	forearm	21–25 (6m)	warm/cold/neutral 2 Peltier elements 40×40 mm	select perceived sensation (7 choices)	- thermal stimulation at one site influences perception of other site (thermal referral) - strong asymmetry between wrist and elbow site
Arai et al. [43]	forearm	20–39 (10m)	hot (44°)/cold (11°)/ neutral (32°) 3 Peltier elements 40×40 mm	report thermal sensation of each spot (hot/null/cold)	- thermal referral: neutral site influenced by neighbor - confusion when one spot hot, other spot cold - confusion with hot/cold/hot or cold/hot/cold pattern - some participants perceived pain at center
Singhal & Jones [44]	forearm	24–29 (1f, 9m)	4 pulses of -8°C, 2 s	localization	- spatio-temporal illusions - second pulse perceived towards third pulse if delay short
Singhal & Jones [45]	forearm	24–36 (10m)	4 pulses of 6°C, 2 s	localization	- spatio-temporal illusions - second pulse perceived towards third pulse if delay short

For participants first the age range is given in years and between brackets the number of participants (f indicates females, m males). dom stands for dominant, ant for anterior, and pos for posterior.

In [44], the authors investigated whether a similar illusion could be created with thermal stimuli. Participants placed their forearm on a device with three Peltier elements with contacts near the wrist, halfway and near the elbow. They tested the perception of various patterns of four cooling pulses (two of the pulses were generated by the same element). They indeed found patterns where the perception of the location of the second pulse was substantially shifted towards the location of the third pulse. In [45] they showed that a similar shift can be found with patterns consisting of warm pulses.

3.7 Thermal Communication

A number of studies investigated the possibilities of thermal devices for communication over a distance (see Table 7). In these experiments mostly couples or families participated and either the wrist [49], [50], the forearm [36], [51], [52], [53] or the waist [54] was the body location used for stimulation. The intention of the devices is often to convey feelings of affection (e.g. [36], [49]) or social presence (e.g. [54]) to the partner or child at a distance. Other studies let the participants free in the use of the device and investigated how and in which circumstances they use the possibility of thermal messaging (e.g. [50], [51], [52]).

A communciation tool termed “Lovelet” [49] gives users information about the temperature of the surroundings of their partner by displaying a certain color on a small LED. If they noticed that their partner was in a cold environment, they could remotely stimulate a Peltier element on their partner’s wrist to warm up. Two couples used this device during 20 days. It was found that the couples also used the device spontaneously during telephone calls or while chatting. In three studies [50], [51], [52], pairs, couples or families, were provided with a prototype thermal device and they were asked to explore the possible use of messaging and to keep track of when and where they used it. In all three studies it turned out that the devices were used in many different ways, such as gaming, wishing good night, secret messaging when others were present, warnings, and wake up calls. They conclude that there is quite some potential for the use of thermal messaging in interpersonal communication.

In [53] participants were given a hand-held device they could squeeze in order to give a thermal stimulus to the forearm of another person, either their partner or a friend. The pairs were seated in different rooms. They were instructed to discuss various specific topics while emphasizing their emotions by using the haptic device. Warm and cold stimuli were consistently used for positive and negative emotions, respectively. The Thermal Array Display (TAD) described in [36] consists of three Peltier elements placed on the volar forearm. In the experiment, all three elements always had the same temperature of either 1°C, 2°C, or 3°C above or below a neutral temperature of 32°C. These thermal stimuli were combined with text messages and participants had to rate the valence of the message and how much they were aroused by it. The valence of the message was not influenced by the temperature of the device, but especially for neutral messages, temperature may influence the emotional arousal of the user.

A thermal harness [54] consisted of a waist belt in which three Peltier elements were placed. Warming up of these Peltier elements was intended to simulate the warmth of the arm of a partner placed around the waist. Pairs of participants always consisted of one male and one female who had been close friends for at least a year. One of the pair (the heatee) wore the belt, the other (the heater) had access to a “thermal hug button” that could activitate the belt. The study showed that thermal stimulation could increase the feeling of social presence between users.

3.8 Thermal Applications

There are a few studies that use thermal stimuli in an application and test performance in controlled experiments (see Table 8). In [55] the authors describe and test a device they termed “WeaRelaxAble”. As the name already suggests, the device is intended to relax stress by means of thermal stimulation (and not discussed here, also audio, light and vibration). Body sites that received warm or cold stimulation were shoulder, loin and groin. The cold stimulation was either not felt at all or perceived as a strange sensation. On the other hand, warm stimuli were rated as pleasant and relaxing. A second experiment in which half of the participants were allowed to actively use the stimulation during a series of challenging tasks did not reveal a significant stress reduction.

In [56] the authors investigated whether thermal stimulation on the forearm by means of a Peltier element is suitable as feedback mechanism in a video game instead of more commonly used vibratory or visual information. They investigated four feedback mechanisms that are often implemented in video games, namely Quick Time Events (QTE; requirement to quickly perform a certain action), Power Bars (PB; stop a changing power value at a preferred level), Cooldowns (CD; waiting time till some ability can be used again) and Area of Effect (AoE; area in which an effect will take place). They conclude that especially QTE and AoE are potentially of interest to use as thermal feedback mechanism in video games, possibly in combination with other means of feedback.

Another game application is the “Heat-Nav”, a thermal device suitable for navigating through a twodimensional maze [57]. Participants wore three Peltier elements on their forearm. After some piloting, the authors found that using just two temperatures (either warm 35°C or cold 29°C) was most effective in guiding the participant through the maze. As in a familiar game, “warm” signalled that they were moving the cursor in the right direction, and “cold” signalled a wrong direction. Although thermal stimulation is rather slow, most participants already noticed cooling or warming of the device and they interpreted this information correctly.

4 CONCLUSIONS

As could have been expected in advance, thermal phenomena like adaptation and spatial summation, that have been reported for hands, fingers and face, were also found for other body parts. However, an important fact that becomes clear from this overview is that thermal sensitivity varies

TABLE 7
Thermal Communication.

Reference	Location	Participants	Stimuli	Task	Outcome
Fujita & Nishimoto [49]	wrist	(2 pairs)	warming the partner	communication	- informal experiment - couples used device over 20 days
Lee & Lim [50]	wrist	6–39 (11; 2 couples, 2 families)	warm or cool messages	families and couples had to choose their own type of use	- exploration of interpersonal communication - usage: ∼4 messages per person per day during 14 days
Lee & Lim [51]	forearm	(2 pairs)	sending or receiving messages	pairs had to choose and report their own type of use	- potentially of interest in interpersonal communication
Lee & Schiphorst [52]	forearm	8–9, 32–41 (7 families)	warm stimulus from parent to child	- interpersonal communication - report experience and context	- usage: ∼3 messages per day during 14 days - used for different purposes - children interpret messages in different ways
Suhonen et al. [53]	forearm	19–30 (10 pairs)	at least 4°C above or below skin temperature	discuss: - happy days - sad event - restaurant questionnaire	- cold signaled negative or disagreement - warmth signaled positive or agreement - stimulation enables emphasizing
Tewell et al. [36]	forearm	(3f, 9m)	7 thermal stimuli: 29 – 35°C combined with 5 text messages	- rate valence - rate arousal	- thermal stimuli cause arousal, but provide no valence - in neutral messages, temperature may influence emotion
Gooch & Watts [54]	waist	(10 pairs)	thermal hug via harness to the other person	questionnaires rate - closeness - togetherness	- difference in social presence between heaters and heatees

For participants first the age range is given in years (if known) and between brackets the number of participants (f indicates females, m males).

TABLE 8
Thermal applications.

Reference	Location	Participants	Stimuli	Task	Outcome
Klamet et al. [55]	shoulder, loin, groin	- 25–45 (8f, 7m) ∼30 (14f, 12m)	Peltier element heat, cold	rate - comfort - relaxation	- half of participants did not notice cold stimuli - heat at loin more pleasant than at shoulder or groin - heat at loin or shoulder more relaxing than at groin
Kotsev et al. [56]	forearm	18–28 (4f, 9m)	±4°C (easy) ±3°C (hard) RoC 1°C/s	play computer game	- RT (easy) > RT (hard) - correct inputs (easy) > (hard) - no effect on power bars, area of effect, cool down
Tewell et al. [57]	forearm	∼32 (3f, 9m)	29°C, 35°C	navigate 4 mazes	- total time shorter with thermal feedback - fewer turns with thermal feedback

Participants: first the age or age range is given in years and between brackets the number of participants (f stands for females, m for males). RoC is rate of change, RT is response time.

widely over the body, with mouth, face and fingers very sensitive, while foot and leg have poor sensitivity [2]. Moreover, the same stimulus presented to different body parts will be perceived as different in intensity [30]. Humans are more sensitive to cooling stimuli than to warming stimuli, but if asked for preferences in, for example, communication, they prefer the warm stimulation. A stronger thermal sensation can be obtained by either increasing the area of stimulation or increasing the intensity of the stimulation (Jones, 2009). As the intensity of the stimulation is summated over the area (i.e. thermal summation), spatial resolution of thermal stimulation is quite poor.

When using thermal stimulation in an application or experiment, it is essential to take all following factors into account, as all of these will influence the results: rate of temperature change, size of stimulated area, and body location. One should also be aware of possible influences of thermal illusionary effects, such as thermal referral (e.g. [42]), where thermal stimulation at one location influences the perception at another location, and the thermal grill (e.g. [46]), where a grid of warm and cold stimulations might create a painful sensation.

Clearly, our knowledge of the potential use of thermal stimulation on other body parts than hands or face is severely limited. Moreover, the studies that have been performed with these devices are usually quite informal. The question is why this is the case. Is this due to technical limitations, lack of interest by researchers, disappointing pilot results or simply because this research field is rather new? We do not know the answer to this question, but fact is in any case that the research field is new. Therefore, we conclude that there is certainly room for further exploration and more rigorous experiments. The present overview provides the knowledge of human thermal perception and information of what has already been tested and published in the literature, needed to make good choices for types of stimulation (e.g., warming, cooling, rate of change of temperature), body regions to be stimulated and number of stimulators.

From what we found, it is clear that thermal devices should not focus on conveying complex messages. Human thermal resolution is rather poor and thermal summation and thermal referral will complicate and thus limit the information detail that can be transmitted within a given time. However, some of the studies on thermal communication (e.g., [49], [50], [52]) showed positive effects of thermal messaging and people seemed to like the thermal stimulation over the (short) period of testing. In communication, warm had positive associations, whereas cold was interpreted as negative. In gaming, performance with thermal feedback improved. Therefore, we conclude that the potential interest of thermal devices lies in the areas of gaming and communication.

ACKNOWLEDGMENTS

The authors have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 780814, project SUITCEYES.

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Annex 2

Representing numerosity through vibration patterns

Myrthe A. Plaisier, Raymond J. Holt and Astrid M.L. Kappers

Abstract—It can be useful to display information about numerosity haptically. For instance, to display the time of day or distances when visual or auditory feedback are not possible or desirable. Here we investigated the possibility of displaying numerosity information by means of a sequence of vibration pulses. From previous studies on numerosity perception in vision, haptic and audition it is known that numerosity judgment can be facilitated by grouping. Therefore, we investigated whether the perception of the number of vibration pulses in a sequence can be facilitated by temporally grouping the pulses. We found that indeed grouping led to smaller error rates indicating that this facilitated the task. This means that temporally grouping vibration sequences allows the sequence to be displayed at a faster rate while it remains possible to perceive the number of vibration pulses.

Index Terms—Numerosity perception, Vibration pulse sequences, perceptual grouping.

◆

1 INTRODUCTION

It is much easier to judge small numbers of items than large numbers of items. It has been shown repeatedly that small numbers of items (< 4) are judged more accurately and more efficiently than larger numbers of items [1], [2], [3], [4]. It has been suggested that this is because small numbers of items are processed through a more efficient cognitive mechanism than counting. This mechanism has been labeled subitizing [5]. Subitizing was first found in visual perception, but more recently it has also been shown to exist in haptic perception [6], [7] and there is evidence that a similar mechanism also occurs in auditory perception [8]. See [9] for a recent review of subtitizing in the various perceptual modalities.

Judging large numbers of items (>4) can be facilitated by clustering these items together into smaller groups [10], [11]. For instance, the six dots on a dice are distributed with a group of three dots aligned on each side of the dice. This spatial arrangement could be recognised making it easier to determine the number of dots. A similar facilitation effect has been shown in haptic perception [12]. When participants were asked to judge a number of spheres in the hand, they were faster and more accurate when the spheres were distributed over the two hands instead of all grasped in the same hand. Generally the idea is that, each subgroup can be subitized and added to the running total. This results in faster response times and higher accuracy than counting all items sequentially. However, it has also been suggested that pattern recognition may play a role in this facilitation. Especially in the case of using fixed dot patterns such as on a dice people might, of course, recognize the pattern [2].

Not all types of stimuli, however, can be subitized. In that case, counting is used also for the smallest numerosities. In a recent haptic study, it was found that spatially grouping items also facilitated numerosity judgment for stimuli that cannot be subitized [13]. However, in that study all items were always presented simultaneously. This was achieved by pressing the fingers simultaneously onto tactile patterns. So grouping items can facilitate haptic numerosity judgment, regardless of whether subitizing occurs for that particular type of stimulus. Would this also be the case of the items to be enumerated are presented sequentially?

In audition, sequential presentation of a number of tones has been used to investigate numerosity perception in a number of studies [14], [15], [8]. When presenting items sequentially, participants might automatically resort to counting. To prevent counting, the items are presented with only short intervals in between. Several of these studies have reported high accuracy and/or fast response times for up to 2 or 3 items. This suggests that a subitizing-like cognitive process plays a role here. Also, one study reported that grouping by varying the frequency of the sound facilitated numerosity judgment [14]. This shows that indeed grouping can facilitate numerosity judgement of sequentially presented items.

There has been one haptic study that used sequential presentation of the items to study haptic numerosity judgment [16]. In that study vibration pulse sequences were used. It was found that judging numerosity became more difficult with smaller time intervals between vibration pulses. They also found that performance did depend on somatotopic distance. In some cases performance was better when the vibration pulses were presented to two fingers of the two different hands than when presented to two fingers of the same hand.

In the current study we also presented numerosity in the form of a series of short vibration pulses. We investigated whether numerosity judgment of a series of vibration pulses can be facilitated by temporally grouping the pulses. Vibration is a type of actuation that is technically easy to

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achieve. It is also present in many personal devices such as smartphones, smart watches and fitness bracelets. Currently, there exists an app that allows displaying the time on a smart watch via a series of vibration pulses (Timebuzz app). Understanding how vibration pulse sequences should be structured to facilitate perception and cognitive processing of the sequence is potentially useful to make such devices more user friendly.

2 METHOD

2.1 Participants

A total of 5 participants completed the experiment. Two of them were authors and three were students of the Department of Mechanical Engineering who were naive as to the purpose of the experiment.

2.2 Setup and stimuli

The hardware consisted of a micro controller (Arduino nano) and a vibration motor (Adafruit mini motor disc). The vibrator was 10 mm diameter and 2.7 mm thick. The vibrator was switched on by providing 5V to the digital pin of the micro controller to which it was connected.

The vibrator was taped to the middle of the volar side of the left forearm of the participant. A vibration pulse lasted 100 ms and there was a 40 ms break between vibration pulses. These time intervals were chosen such that each vibration pulse was clearly noticeable, while the sequence was too fast to be counted reliably. This ensured the task was difficult enough to be able to use the error rates as performance measure. Between groups of vibrations a 200 ms break was introduced. Different numbers of vibration pulses were presented and these could be ungrouped (1, 2, 3 ..9 pulses) or grouped (4, 5, 6 ..9 pulses). The size of a group was 1, 2 or 3 pulses. The different grouping arrangements are shown in Table 1. Each numerosity was presented 10 times ungrouped. Each grouping arrangement was presented 10, 9 or 8 times depending on the number of permutations that existed. We aimed at presenting each permutation equally often, which not always resulted in exactly 10 trials. The experiment consisted of 205 trials per participant.

2.3 Experimental procedure and design

Participants were instructed to verbally report the number of vibration pulses that were presented. The experimenter entered the response into the computer and started the next trial. Participants wore earmuffs during the experiment to remove sounds that were produced by the vibrator. The vibrations were not visible. Two of the participants were not aware of what the maximum number of vibration pulses was.

Prior to starting the experiment participants were presented with a couple of example stimuli until they were comfortable with the task and it was clear that they had understood the task correctly.

The error rate was calculated for each numerosity and grouping configuration. This was taken as the performance measure. Psychometric curve fitting was performed using R package Quickpsy [17].

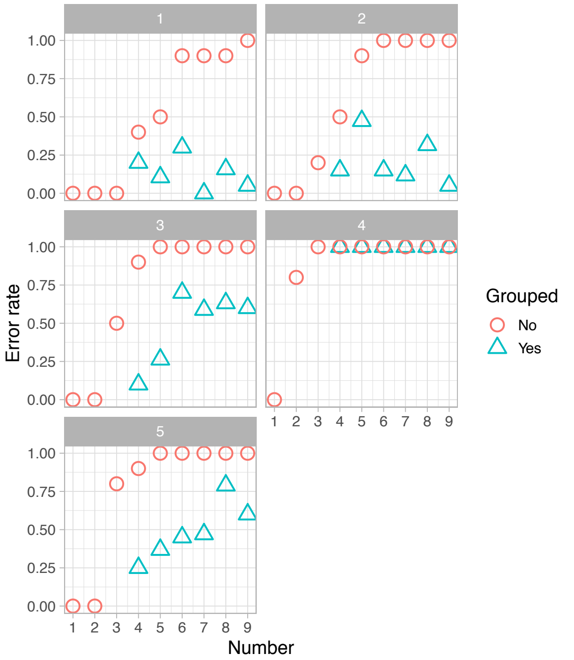

Fig. 1. The error rates as a function of the number of vibration pulses that was presented for the ungrouped (circles) and grouped (triangles) sequences. Each panel shows the data for an individual participant.

3 RESULTS

This was a pilot study to confirm whether participants were able to perform the task, that the vibration sequences were presented fast enough that the error rates did not saturate at 0 or 1 and that the results were consistent across participants. Therefore, we will show the results from each participant individually. As this was a pilot study it would be premature to perform statistical tests. However, a number of systematic effects between participants are clearly visible in the results.

The error rates are shown in Figure 1 for both the grouped (triangles) and ungrouped (circles) vibration pulse configurations. It can be seen that the error rates increased rapidly after 2 or 3 pulses for most participants. Performance for the grouped pulse configurations was considerably better. In Figure 2 the confusion matrices are shown for the ungrouped configurations. Here it can be seen that participants started to systematically underestimate the number of pulses for larger numerosities.

To quantify the numerosity for which there was a transition from easy to difficult, we fitted a psychometric curve to the error rates of the ungrouped configurations and determined the 50% threshold. In Figure 3 it can be seen that this varies between participants (mean = 3.3, sd = 1.2).

It can be seen that the results of participant 4 differ from the pattern in the results of the other participants. This participant already showed systematic underestimation for 2 pulses. Also, the performance for grouped configurations did not show any improvement compared to the ungrouped configurations. Upon debriefing it became clear that the time gap between pulses was too short for this participant to be able to discriminate the pulses, making the task nearly impossible.

TABLE 1
Configuration of the grouped sequences.

Total number of pulses	Subgroup1	Subgroup2	Subgroup3	Subgroup4	Subgroup5	Number of trials
4	2	2				10
	3	1				10
5	2	2	1			9
	3	2				10
6	2	2	2			10
	3	3				10
7	2	2	2	1		8
	3	3	1			9
8	2	2	2	2		10
	3	3	2			9
9	2	2	2	2	1	10
	3	3	3			10

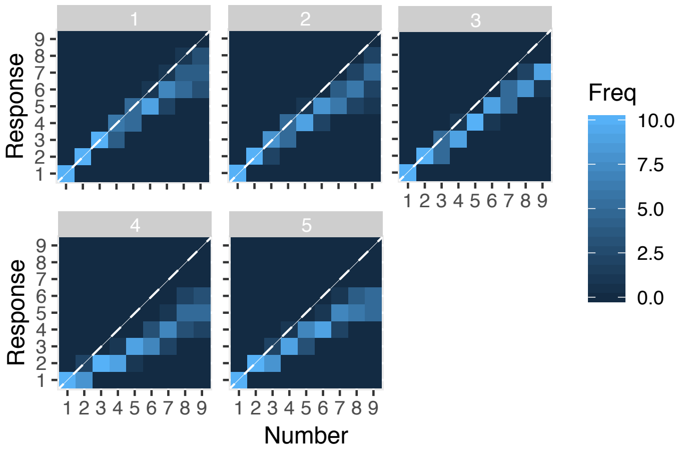

Fig. 2. Confusion matrices for the ungrouped vibration pulse frequencies. The dashed line indicates the identity line. If data is below this line that indicates underestimation of the numerosity.

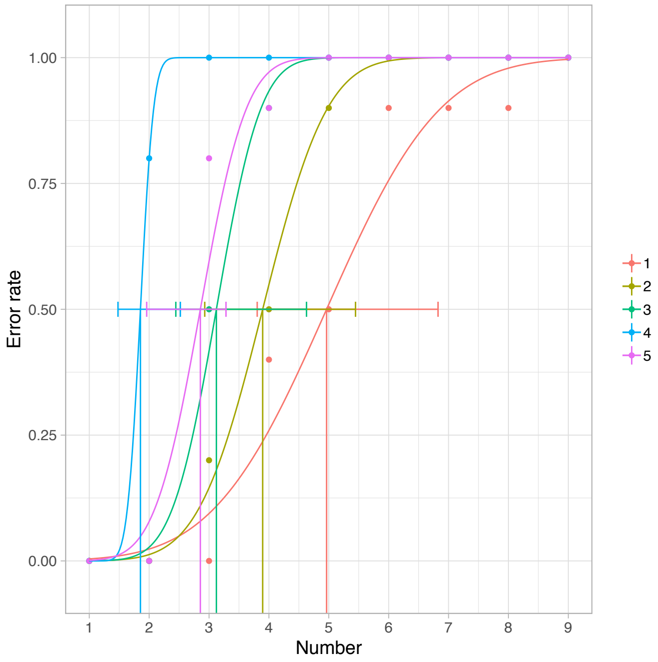

Fig. 3. Psychometric curves fitted to the error rates for each participant individually. The vertical lines indicate the position of the 50% threshold. The error bars indicate the standard error of the threshold.

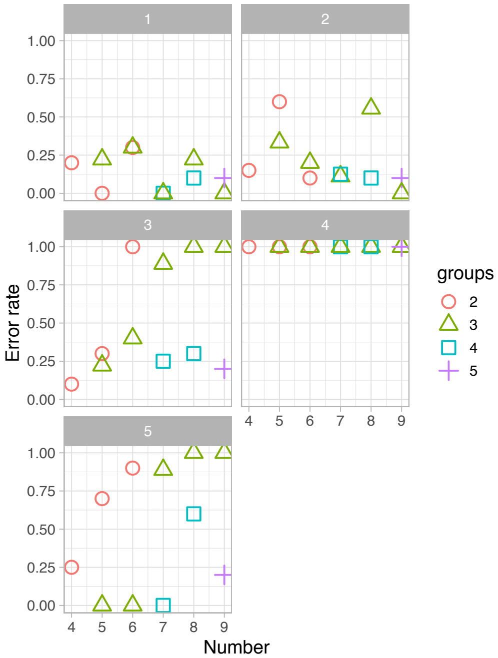

Fig. 4. Error rates for the grouped vibration pulse sequences. Each symbol type indicates the total number of groups. For instance, 6 could be represented with two groups [3,3] or three groups [2,2,2].

For all other participants grouping improved performance considerably. In Figure 4, the performance for the grouped configurations is shown. Here the different symbols indicate the number of groups. For instance, six could be presented with three groups of three pulses or two groups of three pulses. For some participants a smaller number of groups seems to be easier, but not for all.

Participant 4 agreed to perform a second experiment. The experiment was the same except that the time between vibration pulses was now 80 ms, twice as long as previously. Figure 5 shows the results of participant 4 in this second experiment. It can be seen that the results now resemble those of the other participants. The error rates now decreased after three items, instead of after one item in the first experiment (Figure 5a). Also error rates were lower with grouping. Furthermore, the confusion matrix (Figure 5b) is similar to those from the other participants with underestimating occurring for larger numbers of items only.

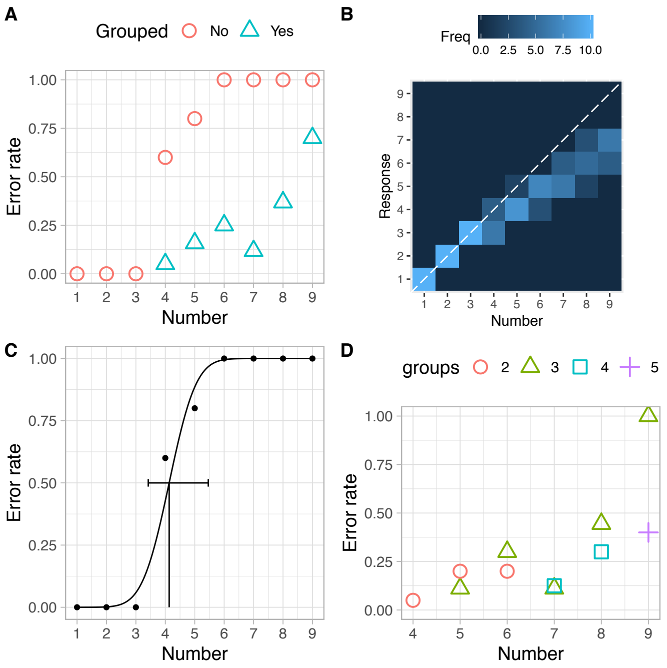

Fig. 5. Data from the second experiment performed by participant 4.

4 CONCLUSIONS

The results from the ungrouped vibration patterns indicate that it became rapidly more difficult to judge the number of vibration pulses for more than 2 or 3 pulses. For the larger numerosities underestimation occurred and for the largest numerosities (8 and 9) participants systematically gave the wrong answer. For participant 4, the results deviated from the others. This participant systematically underestimated the numerosity for any numerosity above 1. This participant indicated that the time between vibration pulses was too small to be able to discriminate between one and two pulses. As a result, also grouping the pulses did not facilitate the task for this participant. When the experiment was performed with a longer time interval between vibration pulses, the results from this participant resembled that from the other participants. This indicates that the temporal resolution for vibration pulses such as presented here varies between individuals.

Grouping increased performance since it led to smaller error rates. However, we did not find a clear dependence of performance on the number of groups presented. What is clear is that judging the number of sequentially presented vibration pulses is facilitated if the sequence is temporally broken up into smaller groups, but what the best way is to brake them up remains to be investigated further

Our results are generally comparable to what has been found for auditory sequences. Auditory studies have found that numerosity judgment became rapidly more difficult for numerosities above 2 or 3 [14], [15], [8]. In the current study, for most participants this was the case as well. In the current study the grouped sequences were longer than the ungrouped ones because there were breaks between the groups. This provided the participant of course with time to process the sequence. However, we made the time between vibration pulses so short that counting during sequence presentation was impossible. This is confirmed by the poor performance for larger numerosities. Therefore, it is more likely that grouping facilitated numerosity judgment through pattern recognition or sequential subitizing. In the final experiment the total presentation time of the sequences of the grouped and ungrouped trials will be controlled.

Overall, our results show that determining the number of vibration pulses in a sequence can be facilitated by temporally grouping the pulses. In practice this means that sequences can be presented faster when they are grouped while still allowing high accuracy in determining the number of pulses. This way numerosity or number information can be communicated faster to the user. Potentially, it also leads to a lower cognitive load, making devices that present vibration pulse sequences less tiring to use.

ACKNOWLEDGMENT

This research was supported by funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 780814, project SUITCEYES.

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Annex 3

Annex 3: Conveying Direction and Distance Using a Single Vibration Motor

Experimental Details

A vibrotactile pattern for delivering radial co-ordinates through a 1-second signal from a single vibration motor was designed such that distance was denoted by the intensity of the signal (a higher intensity denoting a closer point), and direction was denoted by the position of a brief (100ms) gap within a 1 second signal. Directions were defined for seven points across a 180 degree arc in front of the user – such that these corresponded to points on a clock face from 9 o'clock (to the user's left), through twelve o'clock (straight ahead) and then through to three o'clock (the user's right). This gave seven angles from 0 to 180 degrees in 15 degree increments. The angle was denoted by putting a 100ms gap into a 1s vibration, with the position of the gap scaled to the angle being displayed. For example, 9 o'clock was denoted by 150ms vibration, followed by a 100ms gap, then 750ms of vibration to complete the 1s signal. Ten o'clock was denoted by 250ms vibration, followed by a 100ms gap, then 650 ms to complete the signal, 12 o'clock was denoted by 450ms vibration, a 100ms gap, and a further 450ms vibration and so forth. Each signal was presented twice, separated by a 1s gap. Figure 1 illustrates the signals corresponding to different co-ordinates.

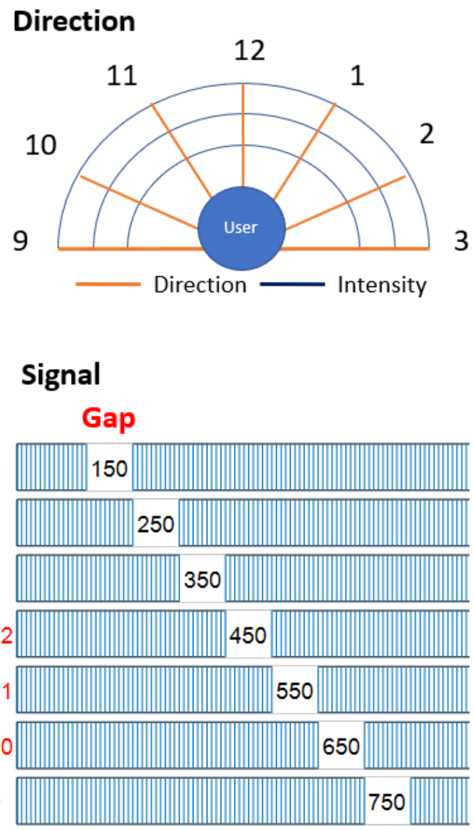


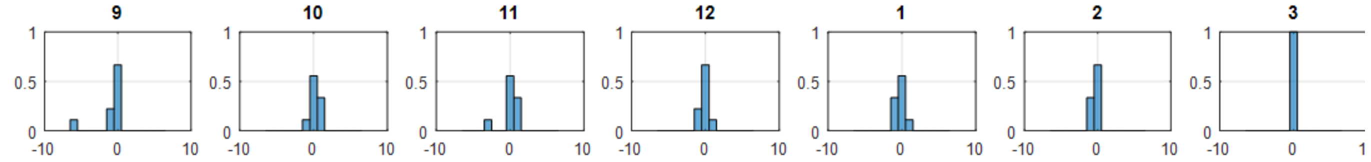
Figure 1 The seven directions available to be displayed, and the corresponding 1s signal with 100ms gap for each direction. The number in the gap denotes how long in milliseconds after the beginning of the signal the gap is positioned.

Intensity was assigned three levels, provided by varying the duty cycle of a 5V pulse-width modulation signal from 70% for the furthest points, 80% for medium-range points, and 100% for the nearest points. No attempt was made to ascribe specific distances to these – at this stage, we were interested only in whether these levels could be reliably discriminated, and whether this affected interpretation of the direction signal.

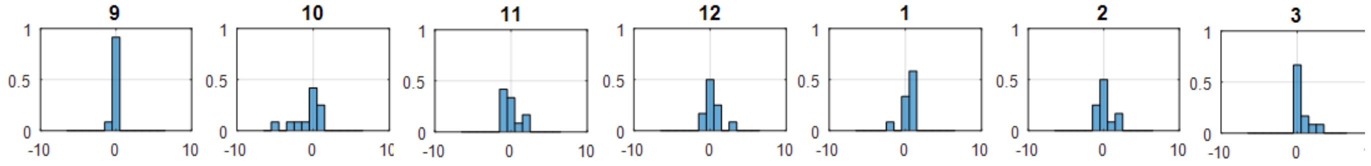
Psychophysical pilot study

To assess whether the coding pattern described above was worth pursuing further, a short pilot study was carried out with three members of the research team. The vibrotactile signals were delivered to the dorsal side of the wrist in each case. This took place in two rounds: first Direction Only, using the patterns shown in Figure 1, but with a fixed PWM Duty Cycle of 80%, then Distance and Direction, in which intensity was varied as well as the position of the gap. Presentations of stimuli were block randomized in each case, with each participant undertaking three blocks of seven trials in the Direction Only experiment, and a single block of twenty-one trials in the Distance and Direction experiment. Error rates across the aggregate results of all participants were identified, as shown in Figure 2, below.

a) Direction Only - Direction Error



b) Distance and Direction - Direction Error



c) Distance and Direction - Distance Error

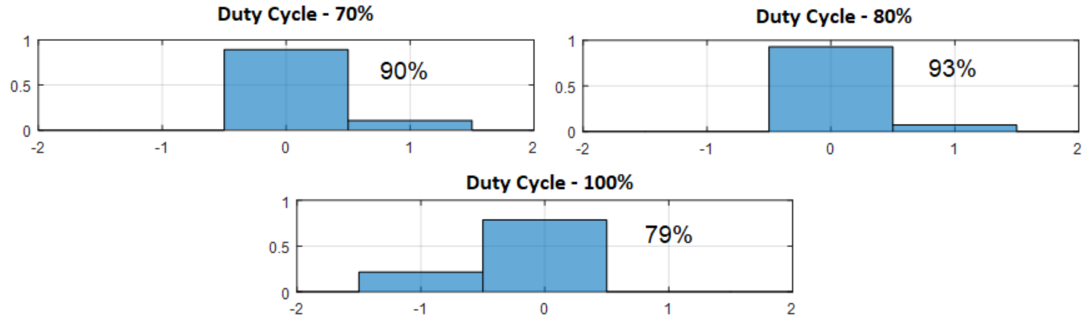


Figure 2: Distribution of Errors for a) Direction only experiment, b) Direction in the Distance and Direction experiment, and c) Distance in the Distance and Direction experiment. Errors denote the number of increments away from the correct response an answer was given – for Direction this denotes the number of "hours" they were incorrect by on the clockface; for Distance how many increments of distance they were incorrect by.

For Direction Only, the results were encouraging: they were generally within one increment of the correct answer. The variation in intensity, however, reduced performance. In general, participants were best at discriminating the ends and the centre of the scale, and errors were generally distributed about zero. Nevertheless, this was sufficiently encouraging to warrant further study, with consideration given to the need for practice and training, and for learning effects. Accordingly, application for ethics approval to conduct a study with naïve participants and a greater number of trials has been made.