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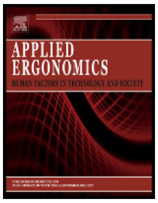

When to use vibrotactile displays? A meta-analysis for the role of vibrotactile displays in human–computer interaction

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ABSTRACT

Objective: This study aims to investigate the benefits of unimodal tactile displays relative to other modal displays and the performance gains of adding redundant tactile displays by integrating empirical studies.
Background: Tactile displays have attracted increasing attention in recent years due to their unique advantages. Synthesizing experimental data is necessary to analyze the performance benefits of tactile displays for participants and better help practitioners in utilizing them.
Method: Five meta-analyses were conducted. Two meta-analyses compared the participants' performance between tactile and other modal displays (visual vs. tactile and auditory vs. tactile). Three meta-analyses examined the performance gains of adding redundant tactile displays based on other modal displays (visual vs. visual + tactile, auditory vs. auditory + tactile, and visual + auditory vs. visual + auditory + tactile). The related moderator variables, the types of presented information and concurrent tasks, were analyzed.
Results: Little evidence shows the performance difference between tactile and auditory displays. Tactile displays are more beneficial than visual displays for presenting alert information or in the situation with a visual concurrent task. The performance gains of adding redundant tactile displays to other modal displays also depend on the specific type of presented information and the concurrent task.
Conclusion: When using tactile displays to convey information, interface designers should consider the specific type of presented information and the concurrent tasks.
Applications: The present study's findings can provide some implications for designers to utilize tactile displays when they construct and implement information displays.

1. Introduction

Although current technologies mainly convey information by visual and auditory displays, tactile displays have attracted increasing attention from researchers and have been often used in human–computer interaction in the past decades. Many researchers use tactile cues to indicate the location of certain targets in the aviation and military fields (Eriksson et al., 2006; White and Hancock, 2020). Vibrating devices are often applied in advanced driver assistance systems of vehicles to convey hazard-related information to drivers for improving driving safety (Biondi et al., 2017; Yang and Ferris, 2020; Zhu et al., 2020). In the area of teleoperation, tactile modality is used to provide feedback information for improving operation performance (Bianchi et al., 2015; Pamungkas and Ward, 2013). Tactile displays have great potential in enhancing the efficiency of human–computer interaction.

Displaying information through the tactile modality has several advantages. First, participants can detect information on the tactile display in the "gaze-free" state. Specifically, the information can be perceived regardless of the participants' eye and head directions (Meng and Spence, 2015; Petermeijer et al. 2017). Second, tactile cues easily draw participants' attention (Ho et al., 2006) and can shorten human response times (Krausman et al., 2007). This characteristic of tactile displays is vital in some emergencies (e.g., the battlefield), wherein a delayed response may bring severe costs. Third, tactile displays can convey information in a more personal and private manner (MacLean, 2008; Petermeijer et al., 2015) because they directly act on the skin and do not disturb others.

Moreover, tactile displays can address the overload of visual and auditory modalities. With the development of various technologies, it has become increasingly common for participants' visual and auditory modalities to be heavily occupied in the data-rich environment with

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various electronic equipment. This condition would result in the overload of visual and auditory modalities (Jones and Safter, 2008), and tactile displays have excellent application potential to address this issue. Multiple resource theory (MRT; Wickens, 2002) indicates that the mental resources are limited and include four dimensions: stages, processing codes, response type, and perceptual modalities. With respect to the dimension of perceptual modalities, information in separate modalities is simultaneously processed without interfering with each other. Conveying information through the tactile modality can distribute processing to different brain regions and offload the visual and auditory modalities (Oviatt, 2017). Therefore, if participants already have visual or auditory tasks, conveying other task-related information via tactile modality is more beneficial than visual or auditory modalities. This condition does not result in resource competition.

However, whether the benefit of unimodal tactical displays can be achieved may depend on the type of information being transferred. In situations that only need simple information to support human activities, such as warning, tactile modality may be feasible to transfer information. Several studies have revealed the performance benefits of tactile modality for presenting warning information. For example, Scott and Gray (2008) demonstrated that tactile warning cues were more beneficial to driving safety than visual and auditory cues, and other researchers found similar results (Hameed et al., 2006; Schmuntzsch et al., 2014). Nevertheless, tactile modality may not be appropriate for transferring complex information (Jones and Safter, 2008), because tactile capacity is much lower than visual and auditory capacities (Reed and Durlach, 1998). “Modal capacity” refers to the amount of information that can be transferred to participants in a certain time (Hsia, 1971). In situations that require complex information to support the human decision and action in a limited time, transferring information only through tactile modality may be awkward. Hence, displaying information solely through the tactile modality may only be appropriate for certain types of information. However, few studies have systematically summarized the influence of the type of presented information on the feasibility of tactile modality relative to other modalities from a quantitative perspective.

In addition, tactile modality is often combined with visual and auditory modalities to construct a redundant multimodal display. This practice can simultaneously guarantee the information transferring capacity and utilize the advantage of the tactile modality. In accordance with multiple resource theory, multimodal displays can expand the bandwidth of information transfer, and each modality does not interfere with others (Wickens, 2002). Thus, combining tactile modality with visual and auditory modalities has a great potential in improving human–computer interaction efficiency, which is demonstrated by some empirical studies. Oskarsson, Eriksson, and Carlander (2012) showed that trimodal cues (tactile + visual + auditory) could remarkably improve pilots' overall performance and perception of threat compared with bimodal cues (visual + auditory). Schmuntzsch et al. (2014) developed a warning glove for users’ assembly error and found that adding tactile warning cues on the basis of visual cues significantly improved performance.

However, some researchers have also found that presenting redundant information by combining tactile modality with other modalities may impair participants’ performance. For example, Lee et al. (2006) found that the combinative redundant warning of visual, auditory, and tactile modalities led to slower reaction times and worse performance. Gibson, Webb, and Stirling (2018) combined visual and tactile modalities to construct a bimodal display conveying surface obstacle information to walkers. The evaluation results showed that the bimodal displays increased head-down and task completion times compared with the visual display. Wickens, Prinet, Hutchins, Sarter, and Sebok (2011) indicated that multimodal information might require more processing time and mental resources to the extent that modalities are not entirely independently processed and in parallel. Hence, such multimodal displays would result in performance loss.

The mixed findings of the abovementioned redundant tactile displays present a challenge for interface designers. An increasing number of studies have investigated tactile modality in recent decades. These studies allow us to conduct a systematic review and meta-analysis for exploring the value of using tactile modality to display redundant information based on other modalities, as well as the benefits of tactile displays relative to other modal displays. The meta-analysis can help designers better determine whether to add redundant tactile displays to other modal displays and when to use tactile displays.

Meta-analysis has several benefits. Meta-analysis can synthesize small sample studies into a large sample to obtain a credible conclusion. It is more powerful than individual studies in terms of detecting small but significant effects (Sutton et al., 2000). Furthermore, meta-analysis can identify the moderator variables, explore the sources of disagreement among studies, observe the whole “landscape” of a research field, and propose meaningful research directions for future work (Rosethal and DiMatteo, 2001). Thus far, only one study has been conducted on the meta-analysis of tactile displays. Prewett, Elliott, Walvoord, and Coovert (2012) conducted meta-analyses by comparing unimodal visual displays with tactile displays and bimodal redundant displays (visual + tactile). The results showed that the overall performance on the visual display condition did not differ from the tactile display condition. Bimodal redundant displays (visual + tactile) could remarkably improve overall performance. However, they only considered visual displays to analyze the value of tactile displays and did not use auditory displays in their study. In addition, the study was conducted approximately 10 years ago, and many new studies have been published in the last decade. Hence, incorporating new evidence in the past decade and systematically conducting meta-analyses are needed to reveal the benefits of tactile displays.

In summary, the present study aims to answer the following two questions:

(1) Question 1: Does the unimodal tactile display have performance benefits compared with the unimodal visual or auditory display? Are the performance benefits moderated by the type of presented information and the concurrent task?
(2) Question 2: Are there performance gains when adding redundant tactile displays on the visual and auditory displays to form multimodal displays? Are the performance gains moderated by the type of presented information and the concurrent task?

To answer Question 1, we conducted two meta-analyses, namely, visual vs. tactile (V vs. T) and auditory vs. tactile (A vs. T). To answer Question 2, we conducted three meta-analyses, namely, visual vs. visual + tactile (V vs. VT), auditory vs. auditory + tactile (A vs. AT), and visual + auditory vs. visual + auditory + tactile (VA vs. VAT). The related moderator variables were also analyzed. The results of these meta-analyses could provide some implications for designers in constructing and implementing information displays.

2. Methods

2.1. Literature search and selection

A literature search was conducted to retrieve as many tactile display studies as possible, including journal papers, conference papers, book chapters, reports, and dissertations. Key terms (tactile, vibrotactile, haptic, touch, modality, multimodal, and cross-modal) were searched in Google Scholar, which is the most comprehensive search engine and is widely used in the review work (Halevi et al., 2017; Martín-Martín et al., 2018). We also searched in some applied journals, such as *Ergonomics, Applied Ergonomics, ACM Transactions on Computer-Human Interac-*

tion, Behaviour & Information Technology, Human–Computer Interaction, Human Factors and Ergonomics in Manufacturing & Service Industries, Human Factors, IEEE Transactions on Human-Machine Systems, Interacting with Computers, International Journal of Human–Computer Interaction, International Journal of Human-Computer Studies, and *International Journal of Industrial Ergonomics*.

Of the 3266 papers searched, 146 papers were retained after examining the titles and abstracts. To avoid missing out on studies that warranted inclusion, we also used some other search strategies, including scanning the reference list in the paper, searching studies that cited a certain paper, and asking fellow researchers for relevant studies (including 48 papers). Then, a thorough reading of the retrieved 194 papers was conducted, and only those papers that met the following criteria were retained for analyses. First, the study had to include at least one of five comparisons, namely, V vs. T, A vs. T, V vs. VT, A vs. AT, and VA vs. VAT (excluding 59 papers). Second, the tactile displays had to be vibrotactile displays, which provided vibration information by actuators (excluding 18 papers). The studies exploring haptic displays were excluded due to the fundamental differences between the haptic and tactile displays on the displaying approach. Specifically, the haptic displays require participants to “actively” act on display first. Then, participants can receive related information, such as braille and haptic steering guidance of vehicles. In comparison, tactile information is “passively” conveyed by actuators (Spence and Ho, 2008). Third, studies had to be conducted through an experimental method (excluding three papers). Studies with questionnaires and interviews without quantitative analysis were excluded. Fourth, the measurement of the experiment had to include objective performance (excluding two papers). Accordingly, those studies that only used subjective ratings were excluded. Fifth, the participants in the study should be without visual or hearing disabilities (excluding five papers). This is because the tactile perceptions of people with visual or hearing disabilities are different from those of people with no disabilities (Röder et al., 2004; Rosenstein, 1957). The present study only focuses on people with no disabilities. Sixth, studies had to provide sufficient statistical information (e.g., means, standard deviations, *t* value et al.) to calculate the effect size and its 95% confidence interval (CI) (excluding 14 papers). Means and standard deviations were also tried to be extracted from figures by using GetData Graph Digitizer 2.26 (http://getdata-graphdigitizer.com/download.php) if not reported in studies. Seventh, the paper should be written in English (excluding three papers). Finally, after removing 19 duplicate papers, 71 papers were considered eligible for subsequent analysis. Fig. 1 presents the whole process of literature search and selection.

2.2. *Coding procedures*

Studies that met the abovementioned inclusion criteria were coded on several dimensions.

2.2.1. *Modality comparisons*

As previously mentioned, five meta-analyses were conducted in the present study (V vs. T, A vs. T, V vs. VT, A vs. AT, and VA vs. VAT). The selected studies were first categorized in accordance with experimental conditions. In particular, a study was simultaneously coded for multiple meta-analyses if it contained multiple comparisons that met our aims.

2.2.2. *Type of presented information*

The type of tactile cues is a vital moderator variable that affects the efficiency of tactile cues (Prewett et al., 2012). This variable can be divided into four specific categories: alert, spatial orientation, feedback, and communication, according to previous studies (Lu et al., 2013; Prewett et al., 2012).

(1) Alert. The tactile modality is often used to convey alert information. The tactile driving collision warning system is a

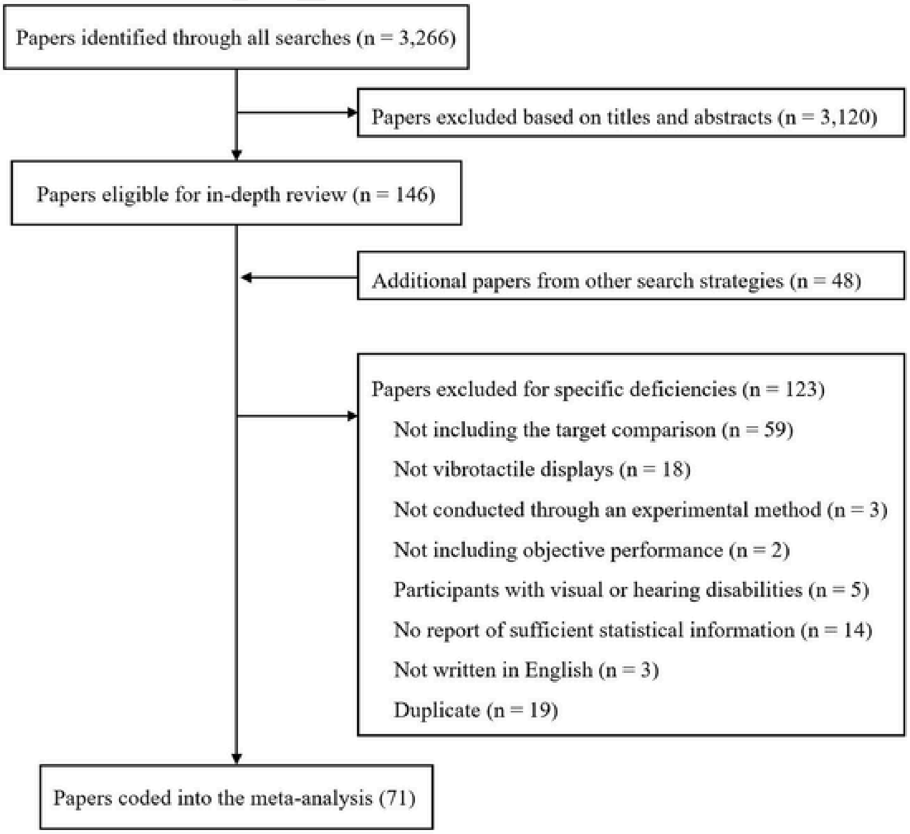

Fig. 1. Flow chart of the inclusion and exclusion process for all papers.

typical application. Many researchers have proposed the use of tactile modality to present driving warning information, and its effectiveness has been demonstrated (Biondi et al., 2017; Ho et al., 2007; Scott and Gray, 2008). Tactile displays are also used to convey alert information in other fields, such as in aviation (McKinley et al., 2007) and industrial assembly (Schmuntzsch et al., 2014).

(2) Spatial orientation. Tactile cues have been widely used to convey spatial orientation information, such as for tactile navigation systems (Davis, 2007; Elliott et al., 2010; Pielot and Boll, 2010) or for indicating target locations (Glumm et al., 2006; Hancock et al., 2013; van Erp et al., 2007). Tactile displays can be a vibrotactile waistband (Elliott et al., 2010), a vibrotactile vest (Riggs and Sarter, 2019), a vibrotactile wristband (Montuwy et al., 2019), or come in other forms. The tactile display can convey corresponding spatial messages by activating actuators on a specific location. Notably, several studies explored the compatibility of spatial cues, indicating that spatial cues did not naturally map to the corresponding orientations in some experimental conditions (e.g., where activation of the left actuators [or a visual cue on the left] indicated the right direction). From these studies, we only extracted the data on the compatible condition, because those counterintuitive spatial cues bring the extra costs of training and learning, which is not the focus of the present study.

(3) Feedback. Providing tactile feedback is another important application of tactile displays. Tactile feedback is widely used in human–machine interactions, such as typing feedback (Suh and Ferris, 2019), interaction gesture feedback (Kopsel et al., 2016), and trunk orientation feedback (Etzi et al., 2020). Its effectiveness has been verified in several studies (Cockburn and Brewster, 2005; Hu et al., 2012; Suh and Ferris, 2019).

(4) Communication. The tactile display can also present communication information through tactile patterns (e.g., duration, localization, intensity, and frequency). Communicative tactile displays are typically used in the military field, because communicating through visual or auditory modalities may be difficult in some circumstances of combat. Several studies have demonstrated the feasibility of tactile communicative displays (Barber et al., 2015; Pettitt et al., 2006).

2.2.3. *Concurrent task*

If participants have to perform a concurrent task other than an ongoing task, their workloads are likely to increase. The modality that the concurrent task occupies affects the performance of the ongoing task. In accordance with multiple resource theory (Wickens, 2002), if the ongoing and concurrent task simultaneously occupies the same modality, the performance of dual tasks will decrease because the tasks compete for the limited resources. Hence, each study was identified to code whether it had a concurrent task. If it had, the occupied modality of the concurrent task was identified and coded.

2.3. *Meta-analytical method*

Five meta-analyses were conducted following the aims of this study. Comprehensive Meta-Analysis (CMA) version 3.0 was used for analysis. Fixed-effects and random-effects models are commonly used in meta-analyses. The fixed-effects model assumes that the actual effect size across all studies is the same, whereas the random-effects model assumes that the actual effect varies from study to study. We chose the latter model in this study based on the assumption that the effect size varied based on the characteristics of each study.

Cohen's *d* was used as the effect size (Borenstein et al., 2011), as it can quantify the effect size on a standardized scale regardless of the original units. In accordance with the guidance of Cohen (1988), the values of 0.2, 0.5, and 0.8 represent small, medium, and large effect sizes, respectively. Commonly, just one effect size is extracted from a single study due to the independence requirement of the data point. When one study conducted multiple separate experiments using different samples, and each experiment had comparisons that we were interested in, we calculated multiple effect sizes in this study. This approach would not violate the independence of effect sizes to a certain extent (Borenstein et al., 2011). Most studies included multiple dependent variables to assess performance (e.g., response time, accuracy, completion time). We averaged the effect size of dependent variables to create a composite effect size according to the recommendation of Schmidt and Hunter (2015). In addition, a 95% CI, which measures the precision of Cohen's *d*, was computed in the present study. It covers 95% of cases in which the population Cohen's *d* falls in the CI. If the CI does not include the null value, the estimated population Cohen's *d* is significantly different from zero (Borenstein et al., 2011). Valentine, Pigott, and Rothstein (2010) indicated that two samples are needed to draw conclusions in a meta-analysis. If some conditions only contained one sample, we did not incorporate that into the analysis and narratively described the effect size of the sole sample instead.

3. Results

Seventy-one papers were included in five meta-analyses. The meta-analysis of V vs. T, A vs. T, V vs. VT, A vs. AT, and VA vs. VAT contained 45, 37, 31, 15, and 15 papers, respectively. Table 1 shows the overall meta-analysis results, Table 2 shows the results of the moderating effect of the type of presented information, Table 3 shows the results of the moderating effect of the concurrent task, and Table 4 presents the summary of significant results across all analyses. In addition, detailed information about the papers included in the analysis is shown in the Appendix.

3.1. *Results corresponding to Question 1*

3.1.1. *V vs. T*

No significant overall performance difference was observed between visual and tactile displays ($d = -0.15$), as shown in Table 1.

The subgroup analysis revealed that the type of presented information had a significant moderating effect on performance ($p < 0.01$). Visual displays had medium performance benefits compared with tactile displays ($d = -0.59$, $p < 0.001$) when presenting spatial information, and the result was reversed ($d = 0.78$, $p < 0.05$) when presenting alert information. No significant difference was observed between visual and tactile displays when presenting feedback and communication information, as shown in Table 2.

The moderating effect of concurrent tasks was significant ($p < 0.001$). When no concurrent task (NCT) was found, visual displays had medium performance benefits ($d = -0.63$, $p < 0.001$) compared

Table 1
Meta-analysis of V vs. T, A vs. T, V vs. VT, A vs. AT, and VA vs. VAT.

Comparison	*k*	*N*	*d*	*SE*	95% *CI*	
					Lower	Upper
Question 1						
V vs. T	50	1012	−0.15	0.12	−0.38	0.09
A vs. T	41	887	−0.05	0.10	−0.26	0.15
Question 2						
V vs. VT	32	740	**0.42*****	0.09	0.24	0.61
A vs. AT	16	436	0.33	0.19	−0.04	0.70
VA vs. VAT	17	360	0.19	0.10	−0.01	0.38

Note. k represents the number of samples. *N* represents the total number of participants. *d* represents Cohen's *d* effect size. *CI* represents the confidence interval for Cohen's *d*. *SE* represents the standard error of Cohen's *d*. Significant Cohen's *ds* are indicated with bold font. ***$p < 0.001$.

Table 2
Moderating effect of the type of presented information.

Comparison	*k*	*N*	*d*	*SE*	95% *CI*	
					Lower	Upper
Question 1						
V vs. *T*						
Alert	7	105	**0.78****	0.32	0.15	1.41
Spatial	24	500	**−0.59********	0.17	−0.92	−0.26
Feedback	11	217	0.09	0.25	−0.39	0.57
Communication	8	190	0.06	0.29	−0.51	0.63
A vs. *T*						
Alert	13	222	0.03	0.20	−0.36	0.41
Spatial	17	450	−0.02	0.17	−0.35	0.32
Feedback	9	159	−0.17	0.23	−0.62	0.28
Communication	2	56	−0.31	0.47	−1.24	0.62
Question 2						
V vs. *VT*						
Alert	5	68	**1.05*****	0.24	0.59	1.52
Spatial	11	291	**0.51*****	0.14	0.23	0.79
Feedback	12	295	0.23	0.14	−0.04	0.50
Communication	4	86	−0.05	0.25	−0.53	0.43
A vs. *AT*						
Alert	5	93	**1.02****	0.38	0.27	1.77
Spatial	4	180	−0.05	0.40	−0.83	0.74
Feedback	5	107	0.18	0.36	−0.53	0.89
Communication	2	56	−0.03	0.57	−1.14	1.08
VA vs. *VAT*						
Alert	3	53	**0.95****	0.28	0.40	1.50
Spatial	5	95	0.24	0.19	−0.13	0.61
Feedback	7	156	−0.01	0.15	−0.31	0.29
Communication	2	56	−0.03	0.27	−0.56	0.51

Note. k represents the number of samples. *N* represents the total number of participants. *d* represents Cohen's *d* effect size. *CI* represents the confidence interval for Cohen's *d*. *SE* represents the standard error of Cohen's *d*. Significant Cohen's *ds* are indicated with bold font. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Table 3
Moderating effect of the concurrent task.

Comparison	*k*	*N*	*d*	*SE*	95% *CI*	
					Lower	Upper
Question 1						
V vs. *T*						
NCT	27	592	**−0.63*****	0.15	−0.92	−0.34
VCT	20	378	**0.60*****	0.17	0.26	0.93
ACT	3	42	−0.81	0.45	−1.69	0.06
A vs. *T*						
NCT	22	524	−0.22	0.14	−0.49	0.05
VCT	16	284	0.09	0.17	−0.24	0.42
ACT	3	79	0.41	0.37	−0.32	1.13
Question 2						
V vs. *VT*						
NCT	21	532	**0.22***	0.11	0.00	0.44
VCT	9	190	**0.86*****	0.18	0.51	1.21
ACT	2	18	0.75	0.39	−0.01	1.51
A vs. *AT*						
NCT	12	345	0.23	0.23	−0.22	0.68
VCT	3	61	0.62	0.45	−0.26	1.51
ACT	1	30	0.56	–	–	–
VA vs. *VAT*						
NCT	12	268	0.00	0.10	−0.20	0.21
VCT	4	80	**0.76*****	0.19	0.39	1.13
ACT	1	12	−0.01	–	–	–

Note. k represents the number of samples. *N* represents the total number of participants. *d* represents Cohen's *d* effect size. *CI* represents the confidence interval for Cohen's *d*. *SE* represents the standard error of Cohen's *d*. Significant Cohen's *ds* are indicated with bold font. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Table 4
Summary of significant results across all analyses.

Comparison	Effect size favoring displays not including tactile modality	Effect size favoring displays including tactile modality
V vs. T (Alert)		0.78
V vs. T (Spatial)	−0.59	
V vs. T (NCT)	−0.63	
V vs. T (VCT)		0.60
V vs. VT (Overall)		0.42
V vs. VT (Alert)		1.05
V vs. VT (Spatial)		0.51
V vs. VT (NCT)		0.22
V vs. VT (VCT)		0.86
A vs. AT (Alert)		1.02
VA vs. VAT (Alert)		0.95
VA vs. VAT (VCT)		0.76

Notes. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

with tactile displays. However, tactile displays had medium performance benefits ($d = 0.60$, $p < 0.001$) when a visual concurrent task (VCT) was found, as shown in Table 3. No significant performance difference was observed between visual and tactile displays when an auditory concurrent task (ACT) was found. The overview of the results is shown in Fig. 2.

3.1.2. *A vs. T*

No significant overall performance difference was found between tactile and auditory displays ($d = -0.05$), as shown in Table 1.

The moderating effect of the type of presented information was insignificant. No significant performance differences between tactile and

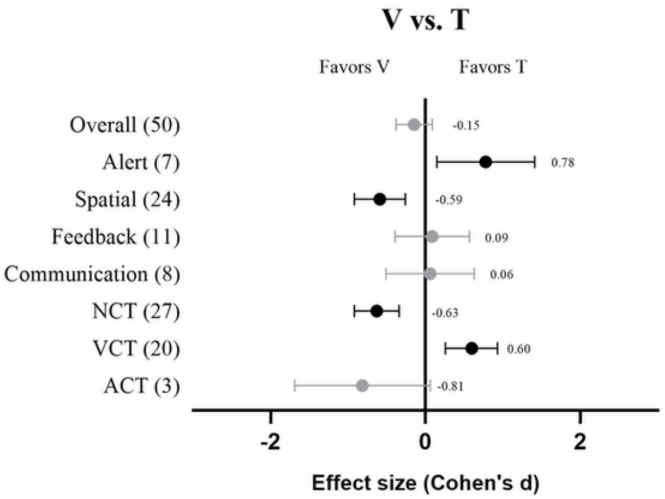

Fig. 2. Overview of the meta-analyzed results of V vs. T. The numbers in parentheses indicate the number of samples. Significant results are represented by black lines, and insignificant results are denoted by gray lines. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

auditory displays was found when presenting alert, spatial, feedback, and communication information, as shown in Table 2.

The moderating effect of concurrent tasks was also insignificant. As shown in Table 3, no significant performance difference was observed between auditory and tactile displays on NCT, VCT, and ACT conditions. The overview of the results is shown in Fig. 3.

3.2. Results corresponding to Question 2

3.2.1. V vs. VT

The results showed that adding a redundant tactile display on the basis of visual displays could significantly improve the overall performance with a small-sized effect ($d = 0.42$, $p < 0.001$), as shown in Table 1.

The subgroup analysis of the type of presented information revealed a significant moderating effect ($p < 0.01$). When presenting alert ($d = 1.05$, $p < 0.001$) and spatial ($d = 0.51$, $p < 0.001$) information, combining the tactile and visual displays could significantly improve performance with a large- and medium-sized effect, respectively. However, no significant performance improvement was observed when presenting feedback and communication information, as shown in Table 2.

The moderating effect of the concurrent task was significant ($p < 0.01$). Adding redundant tactile displays on the basis of visual displays could significantly improve performance when a VCT ($d = 0.86$, $p < 0.001$) and NCT ($d = 0.22$, $p < 0.05$) were found. The performance improvement was insignificant when an ACT was found, as shown in Table 3. The overview of the results is shown in Fig. 4.

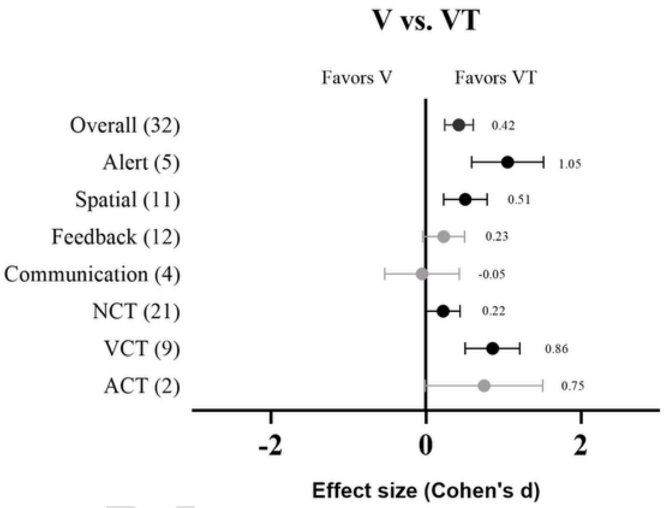

Fig. 4. Overview of the meta-analyzed results of V vs. VT. The numbers in parentheses indicate the number of samples. Significant results are represented by black lines, and insignificant results are denoted by gray lines. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

3.2.2. A vs. AT

The overall performance gains of adding a redundant tactile display on the basis of auditory displays were insignificant ($d = 0.33$), as shown in Table 1.

The moderating effect of the type of presented information was insignificant. Adding redundant tactile displays on the basis of auditory displays could significantly improve performance with a large-sized effect when presenting alert information ($d = 1.02$, $p < 0.01$) but not when presenting spatial, feedback, and communication information, as shown in Table 2.

When testing the moderating effect of the concurrent task, we did not incorporate the ACT condition into the analysis, because the number of samples on this condition was only one. Results showed that the moderating effect of the concurrent task was insignificant. The performance gains of adding redundant tactile displays were both insignificant on the NCT and VCT conditions, as shown in Table 3. The overview of the results is shown in Fig. 5.

3.2.3. VA vs. VAT

The overall performance gains of adding redundant tactile displays on the basis of VA displays to form a trimodal display was insignificant ($d = 0.19$), as shown in Table 1.

The moderating effect of the type of presented information was significant ($p < 0.05$). Specifically, adding a redundant tactile display on the basis of VA displays could significantly improve performance with a large-sized effect ($d = 0.95$, $p < 0.01$) when presenting alert information. However, no significant performance improvement was observed when presenting other types of information, as shown in Table 2.

As the ACT condition only contained one sample, we excluded this in the moderating effect analysis of the concurrent task. Results showed

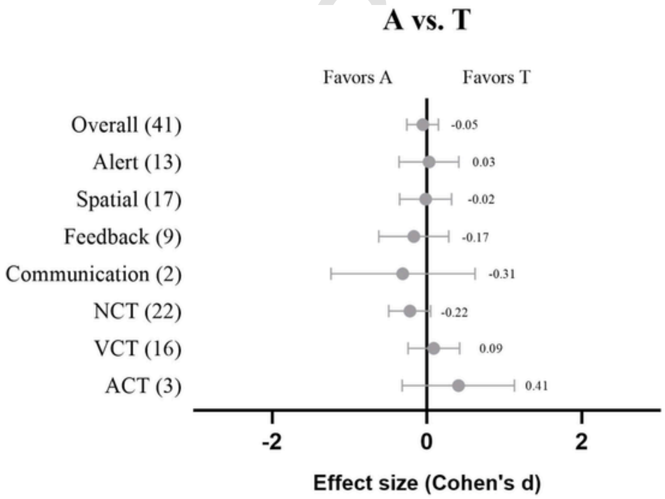

Fig. 3. Overview of the meta-analyzed results of A vs. T. The numbers in parentheses indicate the number of samples. Significant results are represented by black lines, and insignificant results are denoted by gray lines. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

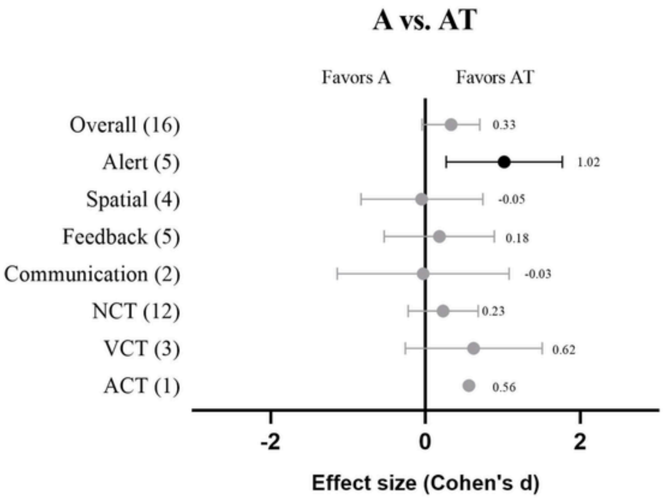

Fig. 5. Overview of the meta-analyzed results of A vs. AT. The numbers in parentheses indicate the number of samples. Significant results are represented by black lines, and insignificant results are denoted by gray lines. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

a significant moderating effect of the concurrent task ($p < 0.001$). Adding redundant tactile displays on the basis of VA displays could significantly improve performance with a medium-sized effect when a VCT was found ($d = 0.76$, $p < 0.001$). However, no performance gain was observed when NCT was found, as shown in Table 3. The overview of the results is shown in Fig. 6.

3.3. Publication bias

Publication bias refers to the phenomenon that studies with statistically significant results are more likely to be published than those with insignificant results (Borenstein et al., 2011). This condition can result in the inflated effect size in the meta-analysis. To test the potential publication bias, we conducted metaregressions to test whether the sample size can predict the effect size (Schmidt and Hunter, 2015). This method requires that 10 studies at least should be included in the meta-analyzed effect size (Higgins et al., 2011). The sample size negatively predicting the effect size indicates publication bias (Schmidt and Hunter, 2015). Compared with large-sample studies, small-sample studies have relatively lower statistical power and obtain significant results less frequently when the effect size is small (Levine et al., 2009). Hence, studies with small sample sizes and small effects sizes are less likely to be published. These unpublished nonsignificant findings will result in the negative relationship between the sample sizes and effect sizes, thus indicating publication bias (Levine et al., 2009). Eighteen metaregressions were conducted (see Table 5). No significant relationship was observed between sample sizes and effect sizes in 15 of 18 analyses. Three of 18 analyses revealed that the effect size could be predicted by sample size in a negative direction with the correlation of −0.52 (V vs. T, VCT), −0.51 (VA vs. VAT, Overall), and −0.62 (VA vs. VAT, NCT). Thus, there was a publication bias in these cases due to the unpublished studies with small sample sizes and small effect sizes. The trim-and-fill technique was used to correct publication bias (Borenstein et al., 2011). This technique assumes that the data points in the funnel plot (a scatter plot of studies' effect sizes against sample sizes, with the effect size as x-axis and sample size as y-axis) are symmetrical in terms of the estimated effect size. When there are unpublished studies with small sample sizes and small effect sizes, the trim-and-fill technique will take three steps to correct this publication bias. First, it trims the data points with small samples and large effect sizes to make the scatter plot symmetrical. Second, it recalculates the "true effect size" (the center of the scatter plot) using the retained data points. Finally, it restores the trimmed data points (studies with small sample sizes and large effect sizes) and adds their counter missing data points (studies with small sample sizes and small effect sizes) symmetrical to the "true effect size". The corrected effect sizes were 0.49 with 95% CI of 0.26–0.73 (V vs. T, VCT), 0.23 with 95% CI of 0.03–0.44 (VA vs. VAT, Overall), and −0.03 with 95% CI of −0.17–0.11 (VA vs. VAT, NCT).

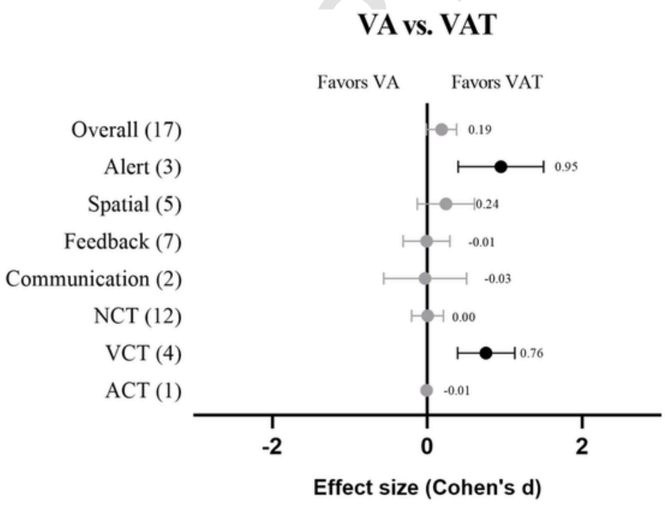

Fig. 6. Overview of the meta-analyzed results of VA vs. VAT. The numbers in parentheses indicate the number of samples. Significant results are represented by black lines, and insignificant results are denoted by gray lines. NCT = No concurrent task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

Table 5
Results of 18 metaregressions.

Comparison	*df*	*F*	*p*
V vs. T, Overall	1, 48	1.13	0.29
V vs. T, Spatial	1, 22	1.81	0.19
V vs. T, Feedback	1, 9	0.16	0.70
V vs. T, NCT	1, 25	1.86	0.18
V vs. T, VCT	1, 18	6.59	0.02
A vs. T, Overall	1, 39	1.33	0.26
A vs. T, Alert	1, 11	0.02	0.90
A vs. T, Spatial	1, 15	0.45	0.51
A vs. T, NCT	1, 20	2.93	0.10
A vs. T, VCT	1, 14	2.57	0.13
V vs. VT, Overall	1, 30	2.46	0.13
V vs. VT, Spatial	1, 9	0.42	0.53
V vs. VT, Feedback	1, 10	0.41	0.54
V vs. VT, NCT	1, 19	0.10	0.76
A vs. AT, Overall	1, 14	0.46	0.51
A vs. AT, NCT	1, 10	0.36	0.56
VA vs. VAT, Overall	1, 15	5.20	0.04
VA vs. VAT, NCT	1, 10	6.24	0.03

Notes. NCT = No current task, VCT = Visual concurrent task, ACT = Auditory concurrent task.

4. Discussion

Tactile displays have attracted increasing attention in recent years in human–computer interaction due to their unique advantages. However, few researchers have systematically reviewed previous studies, and quantificationally analyzed them to reveal the benefits of tactile displays relative to other modal displays. Moreover, whether adding redundant tactile displays on the basis of other modal displays can further improve performance remains inconclusive. To the best of our knowledge, only one study (Prewett et al., 2012) has conducted a meta-analysis on tactile displays. However, it only investigated the role of tactile displays relative to visual displays (V vs. T and V vs. VT) and did not include auditory displays. Moreover, it merely explored the moderating effect of the type of presented information and did not consider the concurrent task, which is of great significance in terms of taking advantage of tactile displays in accordance with multiple resource theory (Wickens, 2002). Thus, the present study further incorporated auditory displays, apart from visual displays, in conducting five meta-analyses to fill these gaps. The moderator variables of the type of presented information and the concurrent task were both analyzed. The results of the present study could provide some reference implications for practitioners to utilize tactile displays when designing human–computer interfaces. The following two sections were organized corresponding to the proposed research questions in the Introduction section.

4.1. Performance benefits of unimodal tactile displays relative to visual and auditory displays

To answer Research Question 1, we conducted two meta-analyses to compare tactile displays with visual and auditory displays in the performance difference. Relative to unimodal visual displays, tactile displays only have performance benefits on some particular conditions. Specifically, tactile displays had large performance benefits relative to visual displays when presenting alert information, which was in line with the findings of

Prewett et al. (2012). However, visual displays were more appropriate in presenting spatial information. This tendency was also revealed in the study of Prewett et al. although it did not reach statistical significance, which may be attributed to the small sample size of their study.

Relative to visual displays, tactile displays can more easily attract participants' attention and be detected regardless of the orientations of the head and eyes, thus facilitating participants' better reaction in an emergency (Meng and Spence, 2015; Petermeijer et al., 2017). For example, in the study of Schmuntzsch et al. (2014), participants were presented with various modal warnings about their maintenance errors in industrial facilities. Tactile warnings resulted in shorter response times than visual warnings. Some visual warnings were even missed by the participants, as their heads and eyes were not oriented to the visual cues when warnings were presented. Krausman, Elliott, and Pettitt (2005) also demonstrated that tactile warnings were effective “attention grabbers” and could shorten soldiers’ response times compared with visual warnings in a combat situation. In terms of spatial information, the approach of tactile displays conveying spatial information in most studies was to activate actuators on a specific location of the body that was naturally mapped to the corresponding orientations (e.g., Pielot and Boll, 2010; Van Erp, and Van Veen., 2004; Elliott2007). Although previous empirical studies have proven that the tactile spatial information conveyed by this approach is intuitive and easy to understand to a large extent (Aaltonen and Laarni, 2017; Li et al., 2015), the present meta-analyzed results indicated that tactile spatial cues are still not as intuitive and comprehensible as visual spatial cues. For example, Davis (2006) and Montuwy et al. (2019) used tactile displays as an alternative to convey spatial information in the navigation system. They found that tactile spatial cues often resulted in longer navigation times and more navigation errors than visual spatial cues, which could be attributed to higher workloads and difficulties in interpreting tactile spatial cues. Therefore, replacing visual displays with tactile displays for presenting spatial information should be performed with caution.

With regard to the moderating effect of concurrent tasks, visual displays were found to have performance benefits relative to tactile displays when there was NCT. By contrast, tactile displays were more beneficial when a VCT was found. For example, in the study of Savick et al. (2008), soldiers were instructed to control and move remote robotic vehicles to specific directions following various modal cues. At the same time, they were required to look for surrounding enemy targets and fire at them (VCT), which heavily depended on their visual resources. The study results revealed that tactile cues significantly outperformed visual cues in helping soldiers control robotic vehicles. Sklar and Sarter (1999) also found that tactile displays were more effective (faster response times and higher detection rates) than visual displays to inform pilots of unexpected mode transitions while they simultaneously monitored traffic conflicts and deviations of an engine parameter (VCT). These findings can be interpreted on the basis of multiple resource theory (Wickens, 2002). When the visual modality of participants has already been occupied, conveying related information of other tasks via visual displays may result in the overload of visual modality and a decline in performance (Prewett et al., 2010). The present study provides the added statistical power to validate the application potential of tactile displays in releasing the visual overload by synthesizing the data of previous empirical studies.

In comparison with auditory displays, no performance benefits of tactile displays were found for presenting alert, spatial, feedback, and communication information. However, tactile displays still provided at least an equivalent performance relative to auditory displays when presenting four types of information from an optimistic perspective. The narrative review conducted by Freeman et al. (2017) proposed that auditory displays could be replaced with tactile displays in some situations wherein presenting related information by the auditory modality is not feasible, such as under noisy circumstances. The present study confirms this proposal and indicates that the replacement would not bring performance costs for presenting related information.

In addition, in accordance with multiple resource theory, presenting information by the tactile modality is more appropriate than the auditory modality theoretically when an ACT is found (Wickens, 2002). Three studies incorporated in the ACT condition all showed this tendency. For example, Hopkins et al. (2017) found that when participants searched for stimulus using various modal cues and simultaneously performed an auditory numerical serial search task (ACT), tactile cues were more effective than auditory cues in terms of search time and accuracy. The studies conducted by Oskarsson et al. (2012) and Mortimer (2006) also revealed a similar tendency. However, the combined meta-analyzed results did not reach statistical significance. This may be attributed to the small sample (3) in the ACT condition.

4.2. Performance gains of adding redundant tactile displays on the basis of other modal displays

With regard to Research Question 2, three meta-analyses were conducted to explore the performance gains of adding redundant tactile displays on the basis of visual, auditory, and VA displays. The results of the three meta-analyses showed that the performance gains of adding redundant tactile displays were a function of the type of presented information. On the basis of visual displays, adding redundant tactile displays could improve performance when presenting alert and spatial information, which was in line with the findings of Prewett et al. (2012). On the basis of auditory and VA displays, the performance gains of adding tactile displays were observed only when presenting alert information. No performance gains were observed for presenting communication information among three meta-analyses, and even there was a tendency for minor performance costs. This condition may be because tactile communication information is commonly expressed by complex vibration patterns of tactors, and it is challenging for participants to distinguish and understand without prior learning and training (Jones and Safter, 2008). For example, the study conducted by Gibson et al. (2018) requires participants to identify and distinguish four vibration frequencies of tactors for understanding tactile communication information. The authors of this study argued that the vibration-to-information mapping was relatively complex so that participants would suffer from the increased mental workload and decreased confidence in perceiving and understanding the tactile information. Hence, sensing and processing tactile communication information may require additional mental resources.

With respect to the moderator variable of concurrent tasks, the results of three meta-analyses showed that adding redundant tactile displays on the basis of visual, auditory, and VA displays could further improve performance when a VCT was found. Although this effect did not reach statistical significance in the meta-analysis of A vs. AT, there was still an evident tendency. In addition, from a quantitative view, the performance gain on the condition of VCTs was greater than that of NCT in the three meta-analyses. On the one hand, this greater performance gain in the meta-analysis of V vs. VT can be interpreted by multiple resource theory. In accordance with this theory, participants have relatively independent modal resources (Wickens, 2002). When participants perform a VCT, adding a redundant tactile display can prevent them from processing information of dual tasks only through the visual modality. For example, participants in the study of Suh and Ferris (2019) were instructed to perform a manual data entry task with visual feedback while simultaneously detecting signages obscured on the roadside (VCT). These two tasks caused competition for visual processing resources. Providing redundant tactile feedback to the data entry task could allow participants to perform dual tasks with independent resources and effectively alleviate the resource competition. Consequently, the data input efficiency and detection task performance were greater with the redundant VT feedback than the visual feedback. Similarly, Salzer and Oron-Gilad (2015) also utilized redundant VT displays to offload participants' visual modality occupied by the flight mission of flying toward particular targets (VCT). The results showed that the participants responded faster and more accurately to VT spatial cues than to visual spatial cues. On the other hand, Wickens et al. (2011) proposed that the advantages of presenting information in redundant multimodal displays will be amplified when participants' workload increases. This proposal was confirmed by the greater performance gains on the condition of VCTs than NCT in the meta-analyses of A vs. AT and VA vs. VAT. When participants perform the related task with auditory information, the VCT will not lead to resource competition in accordance with multiple resource theory; however, it would cause the increase of participants' workload (White and Hancock, 2020).

On the condition of ACTs, greater performance gains of adding redundant tactile displays than NCT should be observed in accordance with the abovementioned theories. However, only one sample contained ACTs in the meta-analyses of A vs. AT and AV vs. AVT. Hence, we cannot obtain the expected results in these two meta-analyses, and more related studies should be conducted in the future.

4.3. Applied implications of tactile displays

The findings of five meta-analyses indicate that using tactile displays as a single modality or a redundant modality to convey information should consider the type of presented information and the concurrent tasks rather than merely focusing on the overall performance differences. When using unimodal displays to convey information, tactile displays only have benefits on some particular conditions relative to visual and auditory displays. For example, compared with visual unimodal displays, using tactile displays only have benefits for presenting alert information and in situations with a VCT. In addition, adding redundant tactile displays on the basis of other modal displays is not always valuable. Adding redundant tactile displays to visual displays does not contribute to the performance improvement for presenting feedback and communication information. Adding redundant tactile displays on the basis of auditory or VA displays is only beneficial for presenting alert information or in the situation with a VCT. Therefore, whether to use tactile displays should be determined in accordance with the specific situations, and this is consistent with the core idea of adaptive interface designs, which is important for optimizing information processing performance (Sarter, 2007; Scerbo, 1996). For example, when designing a driving collision warning system, tactile displays would be a great choice to replace or combine with visual displays for presenting alert messages to a driver, whose visual modality is mainly occupied by the driving task (Sivak, 1996). However, when designing a walker navigation system, tactile displays may not be appropriate to replace visual displays, because the latter outperforms the former for presenting spatial information. Instead, we could improve navigation performance by combining tactile and visual displays to construct a bimodal navigation display.

4.4. Limitations

Although the present study was carefully prepared, there were also several limitations. First, in the moderating effect analysis, the studies included in some conditions were surprisingly sparse. For example, the number of studies that included ACTs only ranged from one to three in five meta-analyses. The number of studies on the condition of presenting communication information was also insufficient. With the limited number of studies in these conditions, the variation of the results would increase, thereby reducing the power to detect the actual effects. It would thus require a larger body of research to investigate further to draw conclusions.

Second, we used a composite effect size by averaging the effect size of different metrics. This practice was because studies in different fields used diverse dependent variables to measure the related effect, and dependent variables considerably varied across studies. If we conducted a meta-analysis for each dependent variable, the number of studies included in each meta-analysis would be extremely limited. Hence, we used a composite effect size based on the recommendation of Schmidt and Hunter (2015). However, this approach would result in some loss of information. Using specific metrics would provide more comprehensive insights into the related effects because each metric may indicate the particular aspect of performance. Therefore, meta-analyses with more specific metrics could be performed if more studies related to tactile displays are conducted in the future.

5. Conclusion

The present study conducted five meta-analyses to integrate the previous experimental results for examining whether unimodal tactile displays have performance benefits relative to other displays and whether adding redundant tactile displays can bring performance gains. The meta-analyzed results showed that (1) tactile displays were more beneficial for presenting alert information or when a VCT was found compared with visual unimodal displays. (2) Tactile displays had no significant performance difference from unimodal auditory displays in most conditions. (3) Adding redundant tactile displays on the basis of visual displays could improve performance for presenting alert and spatial information or when there was NCT or a VCT. (4) Adding redundant tactile displays on the basis of auditory displays could improve performance for presenting alert information. (5) Adding redundant tactile displays on the basis of VA displays could improve performance for presenting alert information or when there was a VCT.

Uncited references

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix.

Table A1
Papers coded in the meta-analysis

Study	Paper type	Comparison	Type of presented information	Concurrent task	Cohen's *d*
Akamatsu et al. (1995)	Journal	A-T	Feedback	NCT	0.44
		V-T	Feedback	NCT	0.31
Bark et al. (2011)	Conference	V-VT	Feedback	NCT	−0.14
Bark et al. (2014)	Journal	V-VT	Feedback	NCT	0.22
Biondi et al. (2017) (exp 2)	Journal	A-AT	Alert	VCT	1.48
		A-T	Alert	VCT	−0.50
Bliss et al. (2010)	Conference	A-T	Alert	VCT	−0.96
		V-T	Alert	VCT	−0.13
Bloomfield and Badler (2007)	Conference	V-T	Feedback	NCT	1.59
		V-VT	Feedback	NCT	1.26
Brewster and King (2005)	Conference	V-T	Communication	VCT	0.89
Calhoun et al. (2002)	Conference	V-T	Alert	VCT	1.50
		V-VT	Alert	VCT	1.34
Chang et al. (2011) (exp 2)	Journal	A-AT	Alert	NCT	3.22
		A-T	Alert	NCT	1.19
Cholewiak and McGrath (2006) (exp 1)	Conference	V-T	Spatial	NCT	−1.80
Cockburn and Brewster (2005) (exp 1)	Journal	A-AT	Feedback	NCT	−0.04
		A-T	Feedback	NCT	0.07
Cockburn and Brewster (2005) (exp 2)		VA-VAT	Feedback	NCT	0.00
		V-VT	Feedback	NCT	−0.01
Davis (2006)	Conference	A-T	Spatial	NCT	−0.49
		V-T	Spatial	NCT	−1.29
Davis (2007) (exp 1)	Report	A-T	Spatial	NCT	−0.98
		V-T	Spatial	NCT	−2.58
de Korte et al. (2012)	Journal	V-T	Feedback	VCT	0.38
di Luzio et al. (2020)	Journal	V-T	Feedback	NCT	−0.41
Elliott et al. (2006)	Report	V-T	Spatial	ACT	−0.45
Elliott et al. (2007)	Report	V-T	Spatial	VCT	−0.17
		V-VT	Spatial	VCT	−0.16
Elliott et al. (2010) (exp 1)	Journal	V-T	Spatial	ACT	−1.15
Elliott et al. (2010) (exp 2)		V-T	Spatial	VCT	0.35
Elliott et al. (2010) (exp 3)		V-T	Spatial	NCT	−0.49
		V-VT	Spatial	NCT	−0.35
Eriksson et al. (2006)	Conference	V-VT	Spatial	ACT	0.91
Van Erp and Van Veen (2004)	Journal	V-T	Spatial	VCT	1.30
		V-VT	Spatial	VCT	3.31
Etzi et al. (2020)	Journal	V-T	Feedback	NCT	0.00
		V-VT	Feedback	NCT	0.00
Forster et al. (2002)	Journal	V-T	Alert	NCT	0.43
		V-VT	Alert	NCT	0.70
Gibson et al. (2018)	Journal	V-T	Communication	NCT	−0.22
		V-VT	Communication	NCT	−0.22
Halabi et al. (2019)	Journal	A-T	Alert	VCT	0.22
Hameed et al. (2006)	Conference	V-T	Communication	VCT	0.06
Hameed et al. (2007)	Conference	V-VT	Spatial	NCT	1.44
Hameed et al. (2009)	Journal	V-T	Communication	VCT	0.09
Hancock et al. (2013)	Journal	A-AT	Spatial	NCT	0.83
		A-T	Spatial	NCT	−0.39
Ho et al. (2005)	Conference	A-T	Spatial	VCT	0.49
		V-T	Spatial	VCT	0.41
Ho et al. (2007)	Journal	A-AT	Alert	VCT	0.28
		A-T	Alert	VCT	−0.44
Ho and Spence (2009) (exp 1)	Journal	A-T	Spatial	NCT	−0.67
		V-T	Spatial	NCT	−0.13
Ho and Spence (2009) (exp 3)		A-T	Alert	VCT	−0.64
Hopkins et al. (2017)	Journal	A-T	Spatial	ACT	0.45
		A-T	Spatial	NCT	−0.21
Hu et al. (2012)	Journal	VA-VAT	Feedback	NCT	−0.16
		V-VT	Feedback	NCT	1.17
Jacko et al. (2004)	Journal	A-AT	Feedback	NCT	0.06
		A-T	Feedback	NCT	−0.19
		VA-VAT	Feedback	NCT	0.01
		V-T	Feedback	NCT	0.12
		V-VT	Feedback	NCT	0.27
Kopsel et al. (2016) (exp 1)	Journal	A-T	Feedback	NCT	−0.49
		V-T	Feedback	NCT	−0.09
Krausman et al. (2005)	Report	A-T	Alert	VCT	−0.58
		V-T	Alert	VCT	0.79
Krausman et al. (2007)	Report	V-VT	Alert	VCT	0.89

Study	Paper type	Comparison	Type of presented information	Concurrent task	Cohen's *d*
Larkin (1983)	Dissertation	A-T	Alert	VCT	1.52
		V-T	Alert	VCT	0.77
Lathan et al. (2002)	Journal	VA-VAT	Feedback	NCT	0.03
		V-VT	Feedback	NCT	0.43
Lees et al. (2012)	Journal	A-AT	Spatial	NCT	0.16
		A-T	Spatial	NCT	−0.26
		VA-VAT	Spatial	NCT	−0.02
		V-T	Spatial	NCT	0.42
		V-VT	Spatial	NCT	0.42
Li et al. (2018)	Journal	A-T	Feedback	NCT	−0.61
		V-T	Feedback	NCT	−0.24
Lindeman et al. (2003)	Conference	V-T	Spatial	NCT	−0.53
		V-VT	Spatial	NCT	0.11
McIlroy et al. (2017)	Journal	A-AT	Feedback	NCT	0.26
		A-T	Feedback	NCT	−0.08
		VA-VAT	Feedback	NCT	0.00
		V-T	Feedback	NCT	0.09
		V-VT	Feedback	NCT	0.15
Mohebbi et al. (2009)	Journal	A-T	Alert	VCT	0.06
Montuwy et al. (2019)	Journal	A-AT	Spatial	NCT	−1.74
		A-T	Spatial	NCT	−3.40
		V-T	Spatial	NCT	−3.97
		V-VT	Spatial	NCT	0.92
Mortimer (2006) (exp 1)	Conference	A-AT	Spatial	ACT	0.56
		A-T	Spatial	ACT	0.23
Ngo et al. (2012) (exp 3)	Journal	VA-VAT	Alert	VCT	2.09
		V-VT	Alert	VCT	1.53
Oskarsson et al. (2012) (exp 1)	Journal	A-T	Spatial	ACT	0.55
		V-T	Spatial	ACT	−0.85
Oskarsson et al. (2012) (exp 2)		VA-VAT	Spatial	ACT	−0.01
Petermeijer et al. (2017)	Journal	A-AT	Alert	VCT	0.15
		A-T	Alert	VCT	−0.29
Pettitt et al. (2006)	Report	V-T	Communication	VCT	1.02
Pielot and Boll (2010)	Conference	V-T	Spatial	NCT	−0.60
Pitts et al. (2012)	Journal	V-VT	Feedback	VCT	0.42
Qian et al. (2011) (exp 2)	Journal	A-AT	Feedback	NCT	0.91
		A-T	Feedback	NCT	0.42
Rau and Zheng (2019) (exp 1)	Journal	A-AT	Communication	NCT	0.03
		A-T	Communication	NCT	−0.32
		VA-VAT	Communication	NCT	−0.11
		V-T	Communication	NCT	−1.27
		V-VT	Communication	NCT	−0.29
Rau and Zheng (2019) (exp 2)		A-AT	Communication	NCT	−0.09
		A-T	Communication	NCT	−0.30
		VA-VAT	Communication	NCT	0.06
		V-T	Communication	NCT	−1.21
		V-VT	Communication	NCT	−0.23
Riggs and Sarter (2019)	Journal	V-T	Spatial	VCT	0.20
		V-T	Spatial	NCT	−5.64
Salzer et al. (2011) (exp 2)	Journal	VA-VAT	Spatial	NCT	−0.35
		V-T	Spatial	NCT	−1.13
		V-VT	Spatial	NCT	−0.23
Salzer and Oron-Gilad (2015)	Journal	V-T	Spatial	VCT	−0.25
		V-VT	Spatial	VCT	0.54
Savick et al. (2008)	Report	A-T	Spatial	VCT	1.53
		V-T	Spatial	VCT	1.36
Schmuntzsch et al. (2014)	Journal	A-AT	Alert	NCT	0.10
		A-T	Alert	NCT	−0.18
		VA-VAT	Alert	NCT	0.95
		V-T	Alert	NCT	1.34
		V-VT	Alert	NCT	0.73
Scott and Gray (2008)	Journal	A-T	Alert	VCT	0.34
		V-T	Alert	VCT	0.87
Sklar and Sarter (1999)	Journal	V-T	Communication	VCT	1.70
		V-VT	Communication	VCT	1.61
Smith et al. (2009)	Journal	A-T	Spatial	VCT	−0.18
Straughn et al. (2009)	Journal	A-T	Alert	VCT	0.29
Suh and Ferris (2019)	Journal	VA-VAT	Feedback	VCT	0.26
		V-VT	Feedback	VCT	0.17
Sun and Ren (2011) (exp 2)	Journal	A-AT	Feedback	NCT	−0.30
		A-T	Feedback	NCT	−0.59
		VA-VAT	Feedback	NCT	−0.34
		V-T	Feedback	NCT	−0.36
		V-VT	Feedback	NCT	−0.22

Study	Paper type	Comparison	Type of presented information	Concurrent task	Cohen's *d*
Telpaz et al. (2015)	Conference	VA-VAT	Alert	VCT	0.28
van Erp et al. (2007)	Journal	V-VT	Spatial	ACT	0.60
Wahn et al. (2016) (exp 1)	Journal	A-T	Spatial	NCT	2.27
		V-T	Spatial	NCT	−1.96
Weber et al. (2011)	Conference	A-T	Spatial	NCT	−0.45
White and Hancock (2020) (exp 1)	Journal	A-T	Spatial	VCT	1.18
		A-T	Spatial	NCT	0.75
		V-T	Spatial	VCT	1.55
		V-T	Spatial	NCT	0.30
White and Hancock (2020) (exp 2)		VA-VAT	Spatial	VCT	1.29
		VA-VAT	Spatial	NCT	0.82
Yang and Ferris (2020) (exp 1)	Journal	A-T	Feedback	VCT	−0.51
		V-T	Feedback	VCT	−0.06

Notes. NCT = No current task, VCT = Visual concurrent task, ACT = Auditory concurrent task, exp = experiment.

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indicate the reference was included in the comparison of V vs. T;
indicate reference was included in the comparison of A vs. T;
indicate reference was included in the comparison of V vs. VT;
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