Vibrotactile Displays: A Survey With a View on Highly Automated Driving

Sebastiaan M. Petermeijer, Joost C. F. de Winter, and Klaus J. Bengler

***Abstract*—The task of car driving is automated to an ever greater extent. In the foreseeable future, drivers will no longer be required to touch the steering wheel and pedals and could engage in non-driving tasks such as working or resting. Vibrotactile displays have the potential to grab the attention of the driver when the automation reaches its functional limits and the driver has to take over control. The aim of the present literature survey is to outline the key physiological and psychophysical aspects of vibrotactile sensation and to provide recommendations and relevant research questions regarding the use of vibrotactile displays for taking over control from an automated vehicle. Results showed that a distinction can be made between four dimensions for coding vibrotactile information (amplitude, frequency, timing, and location), each of which can be static or dynamic. There is a consensus that frequency and amplitude are less suitable for coding information than location and timing. Vibrotactile stimuli have been shown to be effective as simple warnings. However, vibrations can evoke annoyance, and providing vibrations in close spatial–temporal proximity might cause a lack of comprehension of the signal. We describe the sequential stages of a take-over process and argue that vibrotactile displays are a promising candidate for redirecting the attention of a distracted driver. Furthermore, vibrotactile displays hold potential for supporting cognitive processing and action selection while resuming control of an automated vehicle. Finally, we argue that multimodal feedback should be used to assist the driver in the take-over process.**

***Index Terms*—Highly automated driving, human–machine interface, tactile feedback, vibrotactile display.**

I. Introduction

A. Haptic Displays in Car Driving

VISUAL and auditory displays have traditionally been the most common modes of communication between machine and human. There is now an extensive, and still growing, research base on the effects of visual and auditory displays on human performance and behavior [1], [2].

In the past two decades, the potential of tactile displays has been increasingly investigated, with a particular focus on the application areas of tele-operation [1], aviation [2], military [3], and automotive [4]–[6]. Recently, tactile displays have also made their introduction to the automotive consumer market. Examples are an active gas pedal by Nissan Infinity [7], lane departure warning systems by Citroën and BMW [8], and a forward collision warning system by Kia [9]. Petermeijer *et al.* [10] reviewed 70 haptic driver support systems and distinguished between warning systems and guidance systems. The former category typically uses vibrotactile stimuli, whereas the latter category uses force actuation on the steering wheel or gas pedal. Despite these developments, it has been stated that tactile displays are still an underutilized opportunity for presenting information to users [11].

B. The Advance of Automated Driving

It is likely that within a decade or two, highly automated driving will be introduced on public roads [12], [13]. The Society of Automotive Engineers (SAE) defines conditional automation (similar to "highly automated driving" in the BASt definition or "level 3 automation" in the NHTSA definition) as "the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*" [14]. In other words, in highly automated driving, the driver is no longer required to keep the hands/feet on the steering wheel/pedals and is permitted to take the eyes off the road for extended periods. However, when the functional limits of the automation are reached, the vehicle will provide a take-over request and a transition of control from the automation to the driver will have to take place. Thus, after a take-over request, the driver has to mentally and physically get back into the control loop.

The development of driving automation has serious consequences for the design of feedback devices, such as dashboard lights and auditory warnings, because the driver of a highly automated car may be engaged in a non-driving task such as reading, eating, or resting. While sitting in an automated car, the driver is not necessarily in contact with the steering wheel or pedals. The only parts of the car that are in constant contact with the driver are the seat and seatbelt. Tactile displays could grab the driver's attention, without interfering with auditory non-driving tasks like listening to music or talking on the phone. This makes tactile displays particularly suited to complement visual and auditory displays during highly automated driving conditions.

C. Goal of This Research

The aim of the present paper is to review the literature on vibrotactile displays and to provide relevant recommendations

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S. M. Petermeijer and K. J. Bengler are with the Institute of Ergonomics, Technische Universität München, 85747 Garching, Germany (e-mail: petermeijer@lfe.mw.tum.de; bengler@lfe.mw.tum.de).

J. C. F. de Winter is with the Department of BioMechanical Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: j.c.f.dewinter@tudelft.nl).

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and research questions regarding the take-over process in highly automated driving. This paper provides a definition of a vibrotactile display, a brief description of the physiological mechanisms of vibrotactile sensation, an overview of the dimensions for coding vibrotactile information, and a discussion of previous research on vibrotactile displays in human factors research.

II. Some Essentials of the Mechanical and Physiological Aspects of Vibrations

A. *Definition of a Vibrotactile Display*

In their literature review on tactile and multisensory warning signals for drivers, Spence and Ho [8] made a distinction between the terms tactile and haptic. They used the term "haptic" for situations in which the driver is *actively* interacting with technology, whereas tactile stimuli are delivered *passively* [8] and are usually presented by means of vibration motors (so-called tactors). Haptic feedback systems typically provide the feedback forces via the control inputs of a car (i.e., the steering wheel or gas pedal). Haptic feedback systems will not be considered in the present survey, because during highly automated driving it is permitted to have the hands/feet off the steering wheel and pedals. The present paper defines a vibrotactile display as a device that provides vibrations, using actuators, on one or more locations on the human body.

B. *Electromechanical Vibration Motors*

There are several types of tactors available on the market. Most lightweight vibration motors are electrically powered, but there are also some studies [15], [16] that used pneumatically driven tactors. Generally, there are two types of electric vibration motors, namely eccentric mass motors (ERMs) and linear resonance actuators (LRAs), each of which we will describe briefly (and see McGrath *et al.*, [17] for a thorough overview of tactor technology).

ERMs produce vibrations by rotating a mass that is located outside of the rotation axis (i.e., eccentric), thereby causing an unbalanced centrifugal force. ERMs are relatively cheap and easy to control, but the frequency and amplitude usually cannot be controlled independently from each other.

An LRA is a mass-spring system, similar to loudspeakers in which a voice coil actuates a magnet on a single axis. LRAs need alternating current to operate and are therefore somewhat more difficult to control than ERMs, but they do allow independent control of frequency and amplitude. LRAs utilize the resonance effect of a mass-spring system, making them efficient only in a relatively narrow frequency range around their resonance frequency [17].

C. *Physiology of Mechanoreception*

Humans sense tactile stimuli by means of mechanoreceptors in the skin, which are sensory nerve endings that respond to pressure or deformation [18]. The nerves connect the mechanoreceptors to the central nervous system. The sensitivity of a certain body region to tactile stimuli is determined by the amount of receptors in that region. For example, the fingertips and lips are the most innervated areas of the body and therefore the most sensitive [18].

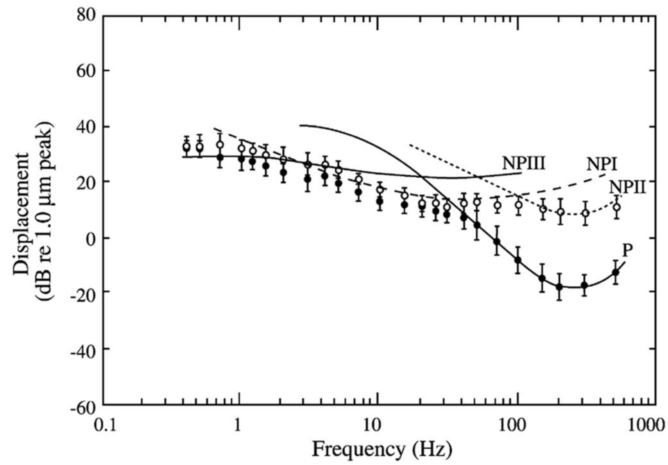

Fig. 1. The four-channel (P, NPI, NPII, and NPIII) model of mechanoreception. Filled markers = experimental data obtained with a large contactor; unfilled markers = experimental data obtained with a small contactor. It can be seen that when a large contactor is used, the absolute thresholds above 40 Hz are determined by the P channel. Taken from Gescheider *et al.* [19].

In the context of information processing, Gescheider, Bolanowski, and Verrillo [19] defined a channel as "an element that is tuned to a specific region of the energy spectrum to which the system responds". Bolanowski, Gescheider, Verrillo, and Checkosky [20] defined four channels of mechanoreception (i.e., P, NPI, NPII, and NPIII), which have different functional characteristics and together cover a wide range of frequencies (0.4–1000 Hz).

The first channel is the Pacinian (P) channel, which is mediated by rapidly adapting mechanoreceptors (i.e., the Pacinian corpuscles) at the nerve endings. The P channel is sensitive to rapid disturbances and high frequency vibrations, and has an U-shaped sensitivity curve between 40 and 800 Hz with its minimum absolute threshold around 250 to 300 Hz [19]. The P channel is capable of temporal summation (i.e., a lower absolute threshold for a longer stimulus duration) and spatial summation (i.e., a lower absolute threshold for a larger stimulus area).

The first non-Pacinian channel (NPI) is mediated by rapidly adapting nerve fibers and Meissner corpuscles. These mechanoreceptors are sensitive across a broad frequency range, with the highest sensitivity at 30–50 Hz. The sensitivity of the NPI channel is relatively unaffected by the frequency, size, and duration of the stimulus [21].

The second and third non-Pacinian channels (NPII and NPIII) are thought to be mediated by slowly adapting nerve fibers. The corresponding mechanoreceptors are Bulbous corpuscles (also called Ruffini endings) and Merkel disk receptors, which are sensitive to stretch of the skin, static pressure, and low frequency vibrations.

Fig. 1 is taken from Gescheider *et al.* [19], and shows the absolute thresholds per channel as a function of stimulation frequency. The P channel has also been called the channel of "vibration" [22] and is thus particularly relevant to vibrotactile applications.

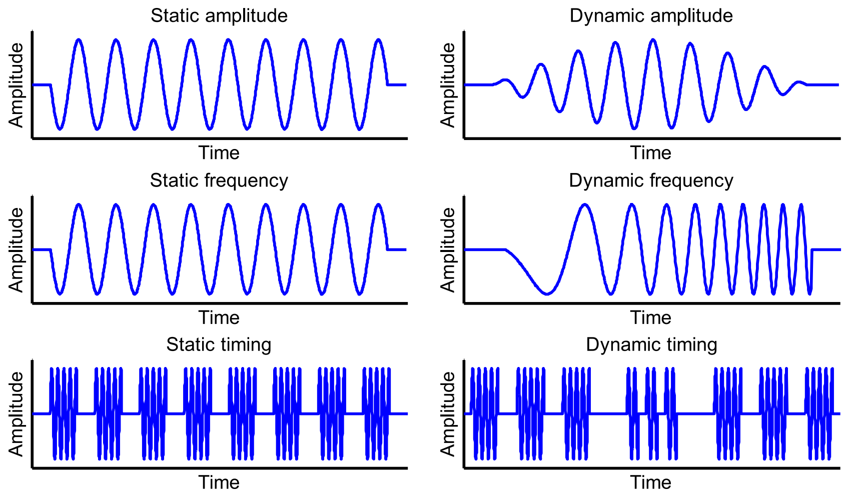

Fig. 2. Illustrations of vibrations with static (left) and dynamic (right) amplitude (top), frequency (middle), and timing (bottom).

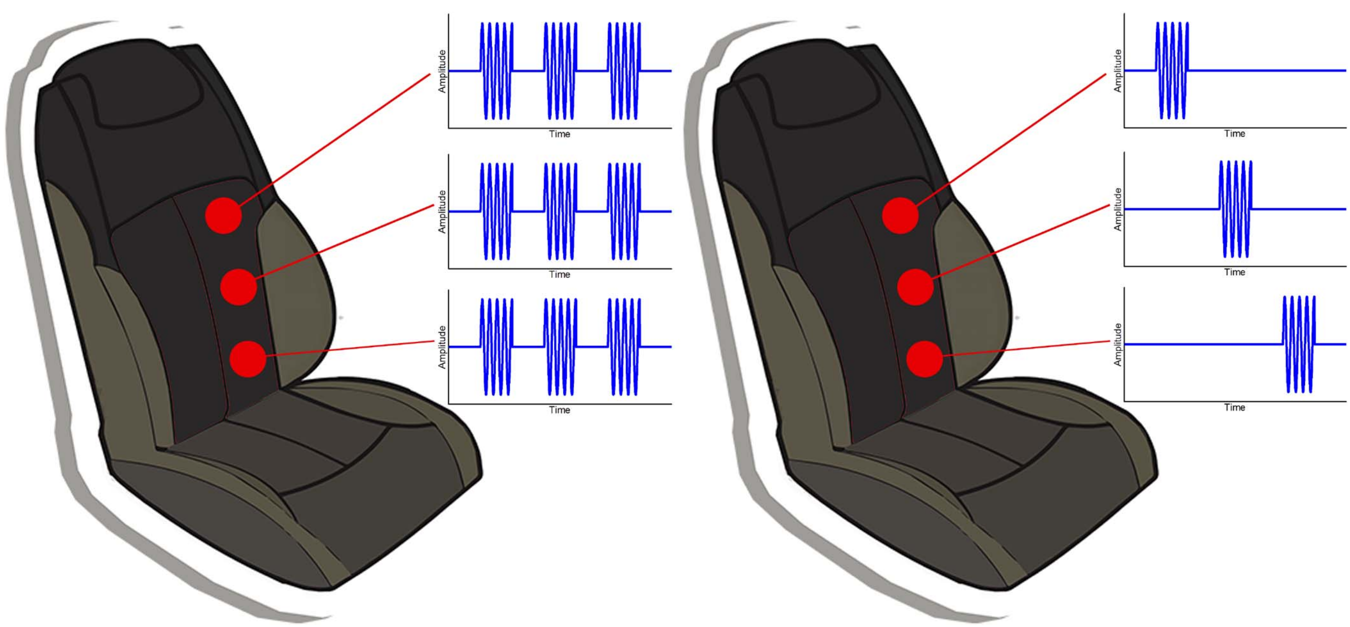

Fig. 3. Illustrations of spatially static (left) and dynamic (right) vibrotactile stimuli. Red circles = locations of activation. Graphs = activation scheme of that particular location. To create a spatially static stimulus (left), the tactors are activated simultaneously. To create a spatially dynamic stimulus (right), different locations are activated in a particular sequence.

III. The Four Dimensions for Coding Vibrotactile Information

In 1960, Geldard [23] distinguished four dimensions for coding vibratory information, namely locus, intensity, duration, and frequency. More recently, Van Erp [24] provided guidelines for vibrotactile displays in human-machine interaction. He essentially distinguished the same four dimensions, but altered the duration of a *single* vibration into the timing (on/off pattern) of *multiple* vibrations. We adopt the following four dimensions: (1) frequency, (2) amplitude, (3) location, and (4) timing (on/off pattern). We further propose that information on each of these four dimensions can be either constant (i.e., static) or varying (i.e., dynamic) over time (see Figs. 2 and 3 for illustrations). Jones and Sarter [11] acknowledged the same four dimensions, whereas Ji, Lee, and Hwang [25] introduced two additional ones, namely the moving pattern (i.e., the activation sequence of tactors) and the direction (i.e., the orientation of tactors). In the present review, we do not explicitly include these additional two dimensions, because we consider "moving pattern" (also known as the phi phenomenon) to be the same as a stimulus with a dynamic location, and because Ji *et al.* [25] did not find a statistically significant difference in the absolute thresholds as a function of the orientation of the tactors.

Several studies, such as Hogema, De Vries, Van Erp, and Kiefer [6], refer to the combination of amplitude and frequency (i.e., power) of a vibration as the "intensity." However, other studies (e.g., [26], [27]) have used the term intensity to indicate amplitude per se. The term "waveform" has also been interpreted in different ways, with some studies [11], [28], [29] interpreting it as the amplitude modulation of a vibrotactile stimulus over time, and others [6], [24], [30] as the shape of the vibrotactile stimulus (e.g., sinusoidal, square, or triangular). Describing a vibrotactile stimulus in terms of the four proposed dimensions, including their dynamic or static properties, could assist in resolving such ambiguities. For example, a "waveform" could be described as a vibrotactile stimulus with a dynamic amplitude.

A. Frequency

As described above, humans are able to detect vibrations between 0.4 and 1000 Hz, with the lowest absolute threshold between 250 and 300 Hz [19], [31] (see also Fig. 1). Van Erp [24] stated that no more than nine frequency levels should be used for coding information. Moreover, Jones and Sarter [11] argued that it is unlikely that humans can distinguish nine different levels when she/he is involved in other activities (e.g., driving). Studies [32], [33] have shown that the perceived frequency not only depends on the exerted frequency, but also on the amplitude of the stimulus.

B. Amplitude

As can been seen in Fig. 1, the absolute threshold is dependent on the frequency of the stimulus. Jones and Sarter [11] summarized the absolute thresholds for several locations on the body. They reported that the lowest absolute thresholds are found at the fingertips (0.07 μm at 200 Hz), whereas the highest absolute threshold was found in the abdomen and glutei (4–14 μm at 200 Hz). The difference threshold (i.e., the detectible change in amplitude) also depends on the amplitude, but it does not follow Weber's law [34].

It has been recommended not to use more than three [11] or four [24] amplitude levels between the detection and pain thresholds for coding information. Vibrations of amplitudes greater than 0.6–0.8 mm will generally evoke a sensation of pain [24]. There is a high variation in the thresholds of pain, not only between humans, but also across an individual's lifetime [24]. Gescheider *et al.* [21] found that the absolute thresholds increase as a function of age. Furthermore, women seem to perceive vibrations more intensely than men do [21], [25].

Using 64 motors with a contactor area of 0.2 cm^2 in a 8×8 grid, Cholewiak [35] showed that the perceived intensity of a vibration increases with the area of stimulation. He investigated this effect for frequencies of 20, 40, 100, and 200 Hz, and the effect seemed to lessen for frequencies below 40 Hz, which could be explained by the NP channels that exhibit no spatial summation. This is consistent with Fig. 1 and Verrillo [36], who showed that, for low frequencies, the absolute threshold is not dependent on the contactor area.

C. Location

The surface area of the skin of a human being is on average 1.8 m^2, which means that there are a large number of possible locations for stimulation. Humans are able to distinguish tactile stimuli that are at least 4 cm apart, for any location on the body. The spatial resolution increases for body parts that are more richly innervated, such as the hands and the face [24].

Geldard and Sherrick [37] delivered five short vibration pulses via three tactors, placed at the wrist, the middle of the underarm, and the elbow, respectively. When the pulses were presented to the locations in sequence with the same inter-pulse time interval (i.e., without disturbing the "rhythm"), the participants did not feel these stimuli at the three locations only, but also experienced a phantom perception of the stimulus, as if it was hopping from one location to the other. This phenomenon has been called the "cutaneous rabbit" [37], and could potentially be used to evoke the feeling of a moving stimulus with a limited number of tactors.

Van Erp [24] mentioned two adverse spatial effects, namely (1) "spatial masking" and (2) "apparent location." Spatial masking is when two stimuli overlap in time but not in location, where one stimulus decreases the detectability of the other [24], [38]. Apparent location is when two stimuli are presented at the same time at different locations, but the human feels one stimulus in one location (in between the two presented stimuli).

Reduced effectiveness of a tactile warning might also occur when there is a multitude of possible warnings that the human could choose from. This phenomenon is also known as Hick's law [39], which states that the decision time of a human increases as a function of the number of response alternatives he can select. Fitch *et al.* [40] attempted to convey up to seven different alert messages to the driver by combining different pulse patterns and stimulus locations. The authors reported the percentage of correct manual responses (e.g., braking or steering), the percentage of correct verbal responses (e.g., "car ahead"), and reaction time (e.g., time between warning and foot of throttle). The participants had to recognize one, three, or seven warning messages in three trials. The correct manual response rate was significantly lower for the three (94%) and seven warning (95%) conditions than for the single warning condition (100%). Similarly, the reaction time was significantly slower for the seven (1.22 s) compared to the three (0.92 s) and single (0.80 s) warning conditions, whereas the verbal response accuracy significantly decreased for the seven (84%) warning condition compared to the three (98%) and single (100%) warning conditions. Fitch *et al.* concluded that up to three separate warnings could be conveyed to the driver without profoundly increasing his workload.

D. Timing

Humans are able to recognize temporal patterns in tactile stimuli with high effectiveness. People can detect vibration pulses and inter-pulse gaps of 10 ms at minimum [41], but seem to prefer pulses between 50 and 200 ms. Longer vibration durations are often perceived as annoying [42]. Both the pulse duration and inter-pulse interval have an effect on the perceived urgency of a signal. The lower inter-pulse interval, the higher the perceived urgency [11], [43]. Between 10 and 150 ms, the pulse duration seems to have a large effect on the perceived urgency (i.e., longer duration is perceived as more urgent) [44]. For pulse durations between 100 and 1600 ms the effect seems to diminish [43].

Presenting two identical stimuli in close temporal proximity at the same location might evoke the feeling that the second stimulus is of greater amplitude than the first. This effect occurs when the two stimuli are presented within 100 to 500 ms of each other. A second effect is temporal masking, which is when a distractor stimulus (e.g., vibrations on a steering wheel as a result of a rough road) interferes with the perception of the timing of a second tactile stimulus on the same location (e.g., a tactile warning signal on the steering wheel). A third temporal effect is neural adaptation, which is the increase of the absolute threshold and the decrease of the subjective amplitude after prolonged stimulation (saturation is gradual and takes up to 25 min for 60 Hz vibrations [45]). A general solution to prevent spatial or temporal masking effects is to use different frequencies for different tactile stimuli [24].

The possibility of conveying messages by means of vibrotactile stimulation has been investigated as well. So-called tactons, equivalent to auditory earcons and visual icons, represent "structured abstract messages that are designed to convey complex concepts and ideas" [11]. Brown, Brewster, and Purchase [46] designed nine tactons based on roughness (i.e., a dynamic amplitude) and temporal pattern. The roughness encoded the priority of the message (i.e., low, medium, high), and the temporal pattern encoded the type of message (i.e., voice call, text message, or multimedia message). The results showed a high recognition rate for both temporal pattern (93%) and roughness (80%). However, it has been argued that the effectiveness of complex tactile messages is probably low in situations where humans are engaged in cognitively demanding tasks (such as driving) [11], [28]. Moreover, learning to distinguish several tactons from each other requires experience or training. Drivers may not be willing to invest the necessary time to learn using new interfaces.

E. Spatio-Temporal Interaction

There is a consensus that the frequency and amplitude dimensions are less suitable for coding information than the location and timing dimensions [11], [24]. However, Van Erp [24] mentioned that spatio-temporal interaction might negatively affect the perception of tactile stimuli. That is, presenting multiple tactile stimuli in close spatial or temporal proximity might lead to so-called tactile clutter [3]. Tactile clutter is a general term that refers to a situation where tactile stimuli are presented at the same or similar time and/or place with the result that humans are unable to distinguish and understand these stimuli.

Tactile clutter could take place, for example, when two tactile messages are provided at the same time. Illustrative for this phenomenon is a helicopter study [3], which showed that a tactile message consisting of two stimuli (one to indicate desired direction of motion, and another to indicate actual direction of motion) was less effective than a simpler version consisting of a single stimulus that reflected the desired direction of motion. The authors argued that the reduced effectiveness of the former interface was the result of tactile clutter.

IV. Vibrotactile Displays in Previous Human Factors Research

A. Vibrotactile Displays Compared to Visual and Auditory Displays in Automotive Applications

The scientific literature of the automotive domain describes a variety of vibrotactile displays. Examples are a lane departure warning system that vibrates the seat pan [47] or steering wheel [48] when the driver crosses a lane boundary, and a forward collision warning system that provides vibrations on the steering wheel [49] or on the waist of the driver [50]. Other applications are a blind spot warning system [51], [52], eco-friendly driving feedback [53], and navigation feedback [54].

Tactile stimuli are less inherent to car driving than visual or auditory ones [6], [8], [28], [54]. Furthermore, it has been stated that tactile stimuli are attention capturing [55], [56] and hard to ignore [24]. That is, tactile stimuli compete less for perceptional resources than visual or auditory stimuli do. Visual stimuli could be missed when these are not in the field of view of the driver, whereas auditory stimuli could be missed when the driver engages in a non-driving auditory task such as talking to a passenger or listening to the radio. These qualities of visual and auditory displays are potentially problematic in highly automated driving, as the driver is not required to keep his eyes on the road and is free to engage in non-driving tasks.

However, suppression effects may be an issue with tactile feedback. An experiment by Gallace *et al.* [57] showed that when participants were turning a steering wheel they were significantly less sensitive to changes in tactile stimuli as compared to show any suppression during movement. Also, tactile stimuli are not absent in car driving. Engine vibrations, an uneven driving surface, or thick clothing, for example, could physically mask a vibrotactile warning when this warning is not salient. However, an intense (i.e., high frequency, high amplitude) tactile stimulus might result in annoyance, discomfort, or pain. Setting the correct intensity of a warning stimulus is a well-known issue and should therefore be carefully considered by interface designers [58].

B. Vibrotactile Stimuli as Warning Message

In the automotive domain, vibrotactile displays are mainly used as warning devices [10]. Two types of warnings are distinguished, that is, non-directional warning, conveying no other information than the presence of the warning itself, and directional warnings, indicating the orientation/location to which the driver should focus his attention. A vibrotactile stimulus provides a directional cue when the proximal stimulus location (on the human body surface) is meant to direct the human's attention to a distal location or direction (see also [26], [28], [59]). For example, it is possible to vibrate the abdomen for signaling a forward collision alert and to vibrate the back of the driver to issue an alert indicating an impending rear-end collision [59].

To evaluate vibrotactile warnings, studies have often used measures of speed (e.g., reaction time or time to return to lane) and accuracy (e.g., error rate, collision rate) [10], [60], [61]. Reaction times are typically measured from the onset of a stimulus to a measurable reaction of the driver (e.g., eyes on the road or steering reaction) [10].

Scott and Gray [50] showed that tactile warnings resulted in faster brake reaction times than visual and auditory warnings of an equivalent temporal (on/off) pattern. Prewett, Elliott, Walvoord, and Coovert [60] found by means of a meta-analysis that non-directional tactile warnings improve task performance of an operator compared to control conditions without any aid (26 studies, Hedges' $g = 1.15$, standard error $= 0.21$, study heterogeneity $I^2 = 78.10$, $p < 0.01$). Moreover, they found that vibrotactile warnings yield performance advantages compared to visual ones (23 studies; Hedges' $g = 0.95$, standard error $= 0.22$, $p > 0.05$). However, there was a substantial variation across effect sizes ($I^2 = 92.02$), suggesting that the effectiveness of replacing visual warnings with vibrotactile ones is dependent on the context in which the warnings are used.

Directional warnings have been used to support the driver in a number of different driving tasks. Beruscha *et al.* [62], for example, provided vibrations on the left or right side of the steering wheel when the driver crossed the lane markings. Nukarinen *et al.* [63] indicated a lane change by vibrating eyeglasses or the seat pan on the right or left side. They found that tactile stimuli evoked faster reaction times than visual ones. Another study [64] used vibrotactile stimuli on the driver's biceps to indicate the direction of a potential collision with a pedestrian or to indicate the direction towards which the driver should steer to avoid the pedestrian. The steering reaction times for early warnings (4.0 s before collision) were significantly faster for tactile feedback than for auditory feedback.

It has been argued that the driver, after receiving a tactile warning, is inclined to visually assess the situation before acting [65], [66]. This suggests that a directional warning can only be more effective than a non-directional one when it assists the driver in visually assessing the situation (e.g., direct the attention towards certain area). Prewett *et al.* [60] stated that tactile directional cues do not significantly improve performance compared to visual directional cues (11 studies, Hedges' $g = -0.20$, standard error $= 0.29$, $I^2 = 90.04$, $p > 0.05$). However, Meng and Spence [28] argued that a spatially dynamic vibrotactile stimulus (see Fig. 2) might be more effective for presenting a warning with a directional cue than a spatially static one.

C. Spatial, Temporal, and Amplitude Dynamic Vibrotactile Stimuli

Van Erp *et al.* [67] showed that tactile stimuli can be used to effectively present navigational information to pedestrians, helicopter pilots, and boat drivers. A tactile waist belt with eight tactors (i.e., separations of 45 deg) was used to indicate the direction of the next waypoint while temporal dynamic stimuli indicated the distance to that waypoint. With a similar algorithm (stimulus location indicating direction, and temporal dynamic stimuli indicating velocity), it has been shown that tactile cues presented on the torso of a helicopter pilot reduced lateral drift [3], [68] and contributed to a performance equivalent to that obtained with augmented visual feedback (a bar indicating the lateral drift) [2]. In their meta-analysis, Prewett *et al.* [60] argued that the effectiveness of tactile displays compared to visual ones is highly dependent on the task and context.

In another study, Van Erp *et al.* [69] showed that a tactile vest can be used to support a pilot to recover spatial orientation faster compared to no tactile support. In this study, the tactile vest provided an artificial horizon to the disoriented operator (i.e., a spatial dynamic stimulus, cf. Fig. 2), reducing the average number of uncontrolled spins per participant from 8 (without tactile vest) to less than 1 (with a tactile vest). In the same way, astronauts might benefit from an artificial vibrotactile cue to determine their orientation [70]. Likewise, Morrel and Wasilewski [71] found that drivers assisted by a vibrating seat showed a small reduction in the amount of time that cars spent in the blind spot of the host vehicle, compared to no assistance. In this study, a 3×5 matrix of tactors was embedded in the driver seat, each column representing a driving lane (i.e., a five-lane scenario). The number of activated tactors would increase when a vehicle came closer to the host vehicle.

Most previous research focused on simple, and often static, vibrotactile stimuli. In the last couple of years, various studies on spatial and amplitude dynamic vibrotactile signals have been conducted. The hypothesis has been that, just like dynamic auditory stimuli (looming warnings) produce an impression of approach, increasing the amplitude of tactile stimuli (cf. Fig. 2) evokes faster braking reaction times compared to stimuli of constant amplitude [28]. However, at least one experiment has shown that increasing the amplitude of the tactile stimulus is not more effective than presenting a stimulus with a constant amplitude [26], [72].

Recent studies [27], [73] have shown that spatially dynamic stimuli can evoke faster reaction times than spatially static ones. A few studies [26], [74] have investigated whether the direction of the stimulus has an effect on driver performance, and have found no statistically significant difference between a stimulus that travelled towards or away from the head (presented at the abdomen of the participant). However, when the inter-stimulus interval was proportional to the closing velocity between the host vehicle and the lead vehicle (i.e., a spatially and temporally dynamic pattern), the towards-the-head stimulus yielded significantly faster reaction times than the away-from-the-head stimuli [26]. Another study [73] showed a statistically significant difference in brake reaction times between a stimulus travelling from the hand towards the body compared to the reverse direction. In summary, it appears that the topics of spatial, temporal, and amplitude-dynamic vibrotactile stimuli are promising, but still relatively unexplored. The results achieved so far require extension and replication.

V. Vibrotactile Feedback in Highly Automated Driving

A. The Relevance of Take-Over Maneuvers in Highly Automated Driving

During highly automated driving the driver does not have to monitor the system permanently, but acts as a backup for the automation. A literature review by De Winter *et al.* [75] showed that drivers who have been out of the control loop for extended periods of time are likely to suffer from degraded situation awareness. If the driver fails to get back into the control loop before the functional limits of the automation are reached, accidents are likely to occur. It is imperative to make the driver aware of the take-over request as early as possible. A well-designed display should, hence, not only make the driver aware of the take-over request, but also assist them in regaining situation awareness.

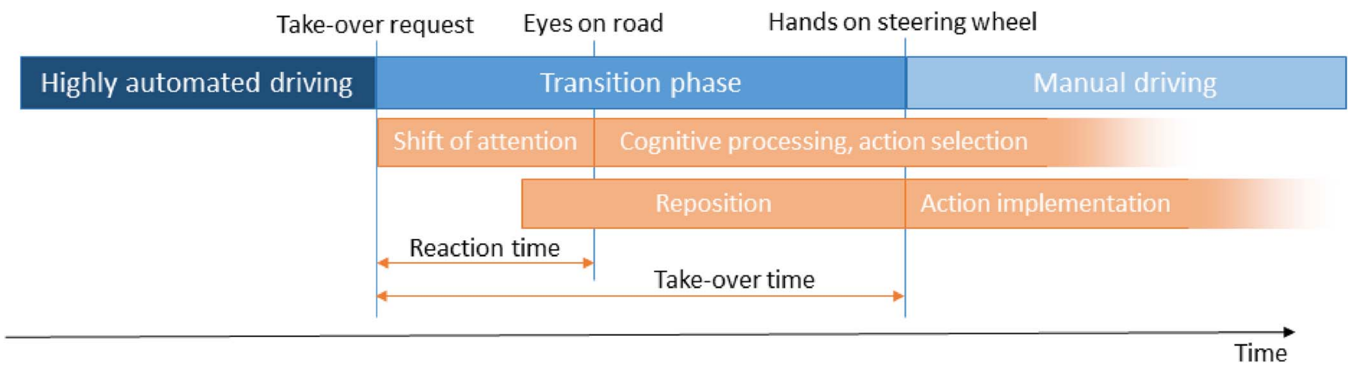

Fig. 4. The take-over process from highly automated to manual driving, adapted from Gold and Bengler [76], Kerschbaum [77], and Zeeb et al. [78].

B. The Temporal Sequence of a Take-Over Maneuver

When the automation issues a take-over request, the driver has to perform several actions, as described by Gold and Bengler [76], Kerschbaum [77], and Zeeb, Buchner, and Schrauf [78]. Getting back into the control loop is a physical as well as a mental process. Specifically, the driver, who may be engaged in a non-driving task, has to:

1) shift visual attention to the road,
2) cognitively process and evaluate the traffic situation and select an appropriate action (i.e., braking or steering),
3) reposition himself, so that control of the vehicle can be resumed (i.e., hands on steering wheel and feet on pedals), and
4) implement the selected action via the steering wheel and/or pedals.

The corresponding temporal sequence is illustrated in Fig. 4. We distinguish three measurable moments in time. The first is the *take-over request*, which is the moment the automation requests the driver to take back control. The second is the *eyes on road*, which is the moment the gaze of the driver first returns to the road after the take-over request. A driving simulator experiment by Gold *et al.* [79] showed that the *eyes on road* reaction time was on average about 0.8 s. In this study, the automation issued an auditory beep to inform the driver that taking over control was required. The third is the *hands on steering wheel*, which is when the driver first touches the steering wheel or pedals again. Gold *et al.* [79] found that drivers made a steering (2 deg steering wheel angle change) or braking input (10% pedal depression) on average 2.1 s after a take-over request with 5.0 s lead time, and 2.9 s after the take-over request with 7.0 s lead time. Similarly, Melcher *et al.* [80] found average reaction times of 3.5 s when a take-over request was provided 10 s before the automation limit was reached.

Note that *shift of attention* versus *cognitive processing, action selection* are described as sequential processes, because one cannot cognitively process a traffic situation without looking at it first. *Reposition* and *action implementation* are also depicted as sequential. However, these two processes can occur in parallel with *shift of attention* and *cognitive processing, action selection*. The driver could, for example, have the initial reaction to press the brakes, and assess the traffic situation only later [76].

The take-over time is unambiguously defined as the time from the take-over request to the moment the driver has his hands on the steering wheel (Fig. 4). Literature indicates that drivers are capable of making a fast decision when needed [79], [81], but it might take tens of seconds to cognitively get back into the control loop, regain situation awareness, and stabilize steering control [82], [83]. Thus, the interval during which the *cognitive processing, action selection* takes place cannot be easily defined in quantitative terms. More research is required in this area in order to obtain valid empirical data on this topic [75].

C. Vibrotactile Displays for the Take-Over Request and Shift of Attention

Vibrotactile displays have been shown to be an effective way of conveying non-directional warnings in a variety of driving tasks [50], [60]. Kosinski [84] reported in a short literature overview that reaction time for a single-choice task to visual, tactile, and auditory stimuli is on average 190, 155, and 150 ms respectively. Hence, vibrotactile stimuli seem, in terms of reaction time, equally effective as auditory stimuli.

Scott and Gray [50] found, in a simulator study, that vibrotactile stimuli presented at the participants' abdomen during manual driving yielded faster brake reaction times than auditory stimuli, but the difference was not statistically significant. A similar result was found by Lee *et al.* [85] with respect to the minimum time to collision (TTC) between auditory and vibrotactile warnings (i.e., higher TTC for vibrotactile stimuli, but not statistically significant). In another study, Mohebbi and Gray [56] showed that warning a driver who was engaged in a conversation was more effective via tactile than via auditory stimuli. Based on these findings, it seems that the reaction time of a driver who is engaged in a visual and/or auditory non-driving task, is probably faster for vibrotactile warnings compared to visual or auditory ones.

Schwalk, Kalogerakis, and Maier [86] investigated spatially static and dynamic patterns to convey a take-over request to the driver. They found that dynamic patterns yielded a higher preference rate. Additionally, they found that older participants showed a reduced recognition rate for all vibration patterns, which is in line with Gescheider *et al.* [21].

After the take-over request has been issued, the driver could be assisted by a directional cue that suggests to where the attention should be directed. Research has shown that it is possible to direct the attention of the driver to two opposite directions (i.e., front vs. back [59] or left vs. right [64]). Moreover, Van Erp [87] showed that with a tactile waist belt, humans can discriminate up to 10 deg in the horizontal plane. However, this perceptual resolution will probably be degraded when humans are engaged in a cognitively demanding task such as a take-over process.

Instead of shifting the attention of the driver to a certain *direction*, it might be possible to communicate a specific *location* on the road for the driver to look at. This would require that the proximal stimulus location on the driver's torso (e.g., seat back, pan, and belt) is mapped to a specific distal location on the road. However, understanding such a message may require a high level of cognitive effort, and therefore a visual check may be more effective in such a situation.

Sufficiently salient stimuli should be used to make the driver aware of a take-over request. There are several approaches to create salient vibrotactile stimuli. One obvious approach would be to provide high amplitude, high frequency vibrations to the driver. However, intense vibrations may cause annoyance and discomfort. A second approach would be to vibrate a large area. This would increase the probability that the driver is in contact with the vibration location even if he/she has an unconventional seating posture. Furthermore, spatial summation of the activated nerve endings (as described above) makes it more likely that the driver detects the stimulus. Note that this approach will be most effective for vibrations above 50 Hz, since only the P channel exhibits clear spatial summation (cf. Fig. 1).

The *shift of attention* takes place in a short period of time (i.e., 0.8 s eyes-on-road reaction time [79]). To be effective, a vibrotactile signal that aims to support the driver during this phase has to be short in duration and intuitively understood by the driver (i.e., without much additional cognitive workload). With this in mind it should be investigated how directional cues are interpreted in a driving context.

D. Vibrotactile Displays for Supporting Cognitive Processing and Action Selection

Vibrotactile displays cannot be used to support the driver in *action implementation*, but could be useful to assist the driver in selecting the appropriate action. After the take-over request has been perceived, the driver needs to regain situation awareness in order to select an appropriate maneuver. Temporal dynamic patterns may be used to indicate the urgency of a traffic situation, whereas spatial dynamic patterns could be used to create an illusion of an approaching hazard. The question remains whether it is possible to make such messages sufficiently intuitive in order for the driver to select an appropriate action. Research should point out whether it is possible to convey semantics, such as *avoid this area* or *steer towards this direction*, with a vibrotactile display [88].

Telpaz *et al.* [89] used a 9 × 3 matrix of vibration motors in the driver seat to inform the driver in which lane cars from the back were approaching during the take-over process. The eye-tracking data showed that drivers checked the mirrors more often when receiving vibrotactile stimuli compared to when they did not receive such tactile stimuli. More research is required into the intuitiveness and perception of dynamic vibrotactile stimuli. For example, a dynamically increasing amplitude and frequency of a stimulus might signal the intuitive meaning of danger, whereas dynamic spatial patterns might indicate a general direction to steer towards. Straughn, Gray, and Tan [64] showed that S-R incompatible (i.e., stimulus on the side of the potential collision) vibrotactile stimuli are more effective for early warnings, whereas S-R compatibility is more effective for late warnings. These results are consistent with Beruscha *et al.* [62] who showed that naive drivers steered away from the vibration location. These authors argued that additional factors, such as a directional cue or the traffic situation, probably have an important influence on the reaction of the driver.

Since the *action selection* phase will generally take longer than the *shift of attention*, there are more possibilities for conveying complex signals to the driver. To assist the driver in selecting a safe maneuver, vibrotactile stimuli in the driver seat could, for example, indicate where other road users are located. It remains to be investigated whether drivers can adequately map the stimulus location to a distal location on the road during the cognitively demanding take-over process.

E. Multimodal Feedback During Take-Over Maneuvers

A multimodal feedback approach may be preferred in many automotive applications, and especially during the take-over process. The meta-analysis by Prewett *et al.* [60] showed that visual-vibrotactile feedback is more effective (regarding e.g., error rate, completion time, and reaction time) than visual-only feedback.

According to the BASt and SAE definitions of levels of automated driving, the driver is required to promptly take over the control of the car after a take-over request, which implies that the driver has to be in the driver seat at all times. However, empirical evidence indicates that drivers in a highly automated car sometimes do leave their seats, for example to grab something from the back of the car [90], [91]. Similarly, auditory stimuli could be missed if the driver is engaged in a non-driving auditory task, like talking on the phone. The human-machine interface should ensure that the take-over request is perceived by the driver regardless of the type of situation. A rough road, thick clothing, or engagement in a non-driving task might cognitively or physically mask a take-over request. Therefore, we recommend that take-over requests should be conveyed by auditory, visual, and/or vibrotactile displays simultaneously, to minimize the likelihood of a miss and to benefit from complementarity and redundancy gain (and see [92]). However, the probability of annoyance might increase when multimodal warnings are used instead of unimodal ones. It remains to be investigated how and in which sequence (multi)modal messages in the four stages of the take-over process should be implemented. Melcher *et al.* [80], for example, combined an auditory take-over request with a visual message on the phone that participants were using during highly automated driving.

Pfromm, Cieler, and Bruder [93] used a LED strip that was affixed 360 deg around in the vehicle's interior to direct the attention of the driver towards relevant objects (e.g., a car coming from the right). They stated that the LED strip was particularly effective (i.e., shorter gaze reaction time) in scenarios where drivers were not looking in the direction of the relevant object. Similarly, auditory feedback could be used to attract the attention of the driver towards a certain direction. However, Fitch *et al.* [94] showed that it can sometimes be difficult to localize the precise location of the origin of a sound.

It is possible that for the different stages of the take-over process (1) *shift of attention*, 2) *reposition*, 3) *cognitive processing, action selection*, and 4) *action implementation*) different modalities are preferred for getting the driver "back into the loop." For example, vibrotactile feedback could be used to shift the attention, after which a visual head-up display could show the danger areas that should be avoided by the driver. This way, one effectively exploits the benefits of the vibrotactile warning (i.e., them being hard to ignore) and of visual feedback (i.e., them being suitable for conveying semantics [28]).

VI. Conclusion and Recommendations

The aim of this article was to review the literature on vibrotactile displays in order to identify relevant research questions and recommendation regarding the use of vibrotactile feedback during the transition of control from highly automated to manual driving. First, a definition of a vibrotactile display and a brief overview of the physiological mechanisms of vibrotactile sensation were provided. Furthermore, we presented an overview of the psychophysics of vibrations and briefly described the four dimensions for coding vibrotactile information. Finally, we described possible applications for using vibrotactile displays in the context of the take-over process in highly automated driving.

Vibrotactile displays are devices that provide vibrations, using actuators, on one or more locations of the human body. Vibrotactile sensation is mediated through four channels, namely the P, NPI, NPII, and NPIII channels, which together are able to detect vibrations between 0.4 and 1000 Hz. Four dimensions are relevant for coding information in a vibrotactile display, namely (1) frequency, (2) amplitude, (3) location, and (4) timing. There is a consensus that location and timing are more suitable for coding information than frequency and amplitude.

Vibrotactile feedback has the benefits that it is hard to ignore, privately conveyed, and easily distinguishable. However, there are several limitations as well, including the human's high difference threshold for frequency and amplitude (i.e., differences in frequency and amplitude often go unnoticed), "tactile clutter" for vibrotactile cues that are presented in close spatio-temporal proximity, and discomfort for vibrations of long duration or high intensity.

This paper introduced four tasks that the driver has to carry out during a take-over process from highly automated driving to manual driving, namely (1) *shift the attention*, (2) evaluate the traffic situation and select an appropriate action (i.e., *cognitive processing and action selection*), (3) *reposition* to physically take over control, and (4) *implement* the selected action.

One of the main challenges in highly automated driving is to get a distracted driver effectively back into the control loop. Vibrotactile displays have the potential to assist the driver during the take-over process. First, vibrotactile stimuli have been shown to be especially effective as warning signals, which should be taken into account with regard to the take-over request. Moreover, we argued that vibrotactile displays have promise to assist the driver in shifting the attention towards a certain direction. Also, vibrotactile feedback might be useful to assist the driver in regaining situation awareness during the *cognitive processing, action selection* phase. Future research should investigate whether spatial and temporal patterns can be used to effectively inform the driver of the traffic situation during this phase.

Finally, we recommend that vibrations should not be used in isolation. As Melcher et al. [80] stated that "a basic HMI strategy, consisting of multimodal (visual and audible), perceivable stimuli is mandatory for Take-Over Requests." We concur that in many cases a multimodal (i.e., visual, auditory, and vibrotactile) display may be the most effective means to assist the driver in the take-over process.

In conclusion, rapid developments in automotive technology will give rise to increasing vehicle automation. However, until the driving task is wholly automated and reliable, drivers will have to take over control at certain instances during their drives. A human-machine interface is indispensable during the take-over process, with vibrations being a particularly promising modality.

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Sebastiaan M. Petermeijer received the M.Sc. degree (*cum laude*) in mechanical engineering from Delft University of Technology, Delft, The Netherlands, in 2014. He is currently working toward the Ph.D. degree in the Ergonomics Department, Technische Universität München, Munich, Germany, working on the HFAuto project. Within this project, he focuses on the haptic human–machine interaction in a highly automated vehicle. Petermeijer won the 2014 Human Factors Prize with the paper titled “Should drivers be operating within an automation-free bandwidth? Evaluating haptic steering support systems with different levels of authority.”

Joost C. F. de Winter received the M.Sc. degree in aerospace engineering and the Ph.D. degree (*cum laude*) from Delft University of Technology, Delft, The Netherlands, in 2004 and 2009, respectively. He is currently an Assistant Professor at the Mechanical Engineering Department, Delft University of Technology. His research interests focus on human factors and statistical modeling, including the study of individual differences, driver behavior modeling, multivariate statistics, and research methodology.

Klaus J. Bengler received the degree in psychology from the University of Regensburg, Regensburg, Germany, in 1991 and the Ph.D. degree in 1995 in cooperation with BMW at the Institute of Psychology (Dr. Zimmer). After his Ph.D. studies, he was active on topics of software ergonomics and the evaluation of human–machine interfaces. He investigated the influence of additional tasks on driving performance in several studies within the EMMIS EU project and in contract with BMW. Multifunctional steering wheels, touch screens, and ACC functionality are examples of the topics of his research. In 1997, he joined BMW. From several projects, he is experienced with experimental knowledge and with different types of driving simulators and field trials. At BMW, he was responsible for the HMI project of the MOTIV program and a national fellow on the program of PROMETHEUS. Within BMW Research and Technology, he was responsible for projects on HMI research and the leader of the usability laboratory. Since May 2009, he has been the leader of the Institute of Ergonomics, Technische Universität München, Munich, Germany, where he is active in research areas such as digital human modeling, human–robot cooperation, driver assistance HMI, and human reliability. He is leading the German Standardization Group (FAKRA) AK-10 “Mensch als Fahrzeugführer” and is an active member of ISO TC22 SC13 WG8 “Road vehicles—Ergonomic aspects of transport information and control systems” as well as a member of the VDI Working Group “Menschliche Zuverlässigkeit.”