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DOI
10.1109/TOH.2015.2437871

Publication date
2015

Document Version
Final published version

Published in
IEEE Transactions on Haptics

The Effect of Haptic Support Systems on Driver Performance: A Literature Survey

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Abstract—A large number of haptic driver support systems have been described in the scientific literature. However, there is little consensus regarding the design, evaluation methods, and effectiveness of these systems. This literature survey aimed to investigate: (1) what haptic systems (in terms of function, haptic signal, channel, and supported task) have been experimentally tested, (2) how these haptic systems have been evaluated, and (3) their reported effects on driver performance and behaviour. We reviewed empirical research in which participants had to drive a vehicle in a real or simulated environment, were able to control the heading and/or speed of the vehicle, and a haptic signal was provided to them. The results indicated that a clear distinction can be made between warning systems (using vibrations) and guidance systems (using continuous forces). Studies typically used reaction time measures for evaluating warning systems and vehicle-centred performance measures for evaluating guidance systems. In general, haptic warning systems reduced the reaction time of a driver compared to no warnings, although these systems may cause annoyance. Guidance systems generally improved the performance of drivers compared to non-aided driving, but these systems may suffer from after-effects. Longitudinal research is needed to investigate the transfer and retention of effects caused by haptic support systems.

Index Terms—Driver assistance systems, warnings, haptic guidance, automotive, automation, human-machine systems

1 Introduction

In the 1960s, Fenton [1],[2] introduced a haptic feedback control stick that aided drivers in a car-following task. The results of these two studies showed that the haptic system reduced headway and speed variance. In 1990, Janssen and Nilsson [3], as part of the generic intelligent driver support (GIDS) project, introduced a haptic gas pedal that exerted a counterforce when the driver adopted a small time headway (THW). This system appeared to have positive effects on the car-following performance of the driver, but participants subjectively judged the system as undesirable. Later, Michon [4] stated that the GIDS-concept may have been ahead of its time, and in the following years little research on haptic support systems was done. Around 2000, a wide variety of Advanced Driver Assistance Systems were introduced to the market, ranging from systems that partially automate the driving task (e.g., adaptive cruise control) or inform the driver through warning signals (e.g., a blind spot warning system). Car manufacturers also released several haptic systems on the market, such as the lane keeping assistance system (LKAS) by Volvo in 2012 and haptic gas pedal feedback by Nissan (Distance Control Assist System) in 2007.

Haptic support systems have been investigated for a variety of driving tasks. There are haptic systems that support the human in driving subtasks, such as lateral control [5], car-following [6], navigation [7], and eco-driving [8]. Furthermore, there are various channels through which the haptic systems can communicate with the driver, such as the steering wheel or seat. Haptic systems may support the driver at different levels of automation, as defined by Parasuraman et al. [9]. Some systems use binary warnings to inform the driver that he/she is too close to a lead car, whereas other systems suggest an appropriate action (i.e., to decelerate) by applying a counterforce to the gas pedal [10].

Studies investigating haptic feedback have used different experimental setups and have evaluated different parameters. For example, some studies have focused on the modality of the signal, such as Navarro et al. [11], who compared visual, auditory, and haptic feedback, whereas other studies have evaluated the effect of different levels of haptic authority within a system, such as Mulder et al. [12]. The level of haptic authority has been defined by Abbink et al. [13] as "how forceful the human-automation interface connects human inputs to automation inputs". That is, they varied the stiffness around a optimal control input to vary the level of haptic authority.

There is an ample body of literature on haptic support systems, but a synthesis concerning the effectiveness of such systems is lacking. The aim of this article is to provide an overview and to investigate the effectiveness of the different haptic system designs. Specifically, three questions will be answered:

1) What haptic systems are currently available or being developed?
2) How are these haptic systems evaluated?
3) What are the effects of these haptics systems on driver performance?

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Manuscript received 2 Feb. 2015; revised 17 May 2015; accepted 21 May 2015. Date of publication 1 June 2015; date of current version 11 Dec. 2015.
Recommended for acceptance by K. Drewing.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TOH.2015.2437871

Note that this article focuses on the research described in the scientific literature. Although several haptic systems are already available on the market, formal evaluations by car companies are normally not disclosed to the public and therefore could not be included in this literature survey.

2 METHOD

An extensive literature search was performed by the authors between November 2012 and April 2013. First, general searches in the databases of Scopus, Web of Science, and Google Scholar using the keywords haptic feedback, shared control, driver support, driver assistance, haptic guidance, and haptic warning were performed. Additional literature was retrieved through the reference lists of the acquired papers. In September 2014 and May 2015, new searches using the same keywords were conducted to identify the most recent literature.

The abstracts of the articles were read to verify whether the publications fulfilled all of the following inclusion criteria:

1) The study was published in a scientific journal or conference proceedings.
2) Participants drove a vehicle in a real or simulated environment, experiencing the locomotion of a motorized road vehicle.
3) The participants were able to continuously control the heading and/or speed of the vehicle.
4) A haptic signal was provided to the driver using a feedback motor. The haptic feedback was dependent on a variable (e.g., speed or time to lane crossing) that represented the physical state of the vehicle in its environment.
5) The system was designed to support the driver in a specific driving task (e.g., lane keeping or eco-friendly driving).

We evaluated the design of the haptic systems at four levels, namely:

1) *Function* is the manner in which the system was intended to assist the driver in a particular driving task (e.g., warning the driver).
2) *Task* describes the driving task for which the system was designed to assist the driver (e.g., lane keeping or navigation).
3) *Channel* is the part of the car that transferred the haptic signal between system and driver (e.g., the steering wheel or seat).
4) *Signal* describes the type of haptic information that the system provided to the human (e.g., continuous force feedback or vibrations).

Finally, we described the effects of the haptic feedback systems on driver performance.

3 RESULTS

3.1 Search Results

The literature search resulted in a large number of journal and conference papers that were of potential Interest. Of these studies, 70 met the inclusion criteria. Three of the 70 studies included two independent experiments that were conducted with different participants [14], [15], [16]. Two articles [17], [18] were found that evaluated the same experiment (thus also same participant set). One [17] of the two studies has been taken into account in the result section of this paper. Of the 70 studies, 41 were available in scientific journals and the remaining 29 were available in conference proceedings.

3.2 Study Characteristics

A total of 1,907 (490 female, 1102 male, 315 no gender reported) unique individuals participated in the 70 studies. The average number of participants per experiment was 27, with 20 experiments using 15 participants or fewer, 34 experiments using between 16 and 25 participants, and 19 experiments using 26 participants or more.

Of the 70 studies, 10 were conducted in real vehicles [15], [17], [19], [20], [21], [22], [23], [24], [25], [26], 11 were conducted in a high-fidelity simulator [8], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], 26 were conducted in a medium-fidelity simulator [5], [6], [7], [11], [12], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], and 23 were conducted in a low-fidelity experimental setup [14], [16], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78]. A simulator was considered to be high fidelity when it used a moving base. A simulator was considered of medium fidelity when it had a wide field of view (more than 120 degrees) but no motion base. Desktop-based setups were considered to be low-fidelity simulators. In low-fidelity simulators, the input device was typically a desktop-mounted steering wheel, including brake and gas pedals. The same categorization of simulator fidelity levels was used by de Winter et al. [79].

3.3 Outcome Measures

3.3.1 System Design

a) Function. After evaluating the included studies we distinguished two functions: warning and guidance. Warning systems were defined as systems that:

- Activate when a threshold is exceeded of an external variable that represents the vehicle position on the road (e.g., deviation from road centre) or relative to another vehicle (e.g., THW);
- Inform the driver about an inadvertent situation, but do no assist the driver to make an appropriate action; and
- Apply a binary (i.e., on/off) feedback. In other words, the feedback is activated as a result of exceeding the aforementioned threshold.

Examples of warning systems are devices that activate when the driver crosses a lane marking [29] or follows a lead vehicle too closely [37]. The system warns the driver by a signal such as a vibration on the steering wheel. Note that vibrations can come in pulse trains (i.e., temporally spaced on/off patterns). The benefits and limitations of warning systems have been extensively discussed in the literature [80], [81]. Probably the most important design challenge is to determine the appropriate threshold value. An early warning (i.e., a false alarm) is likely to result in disuse of

TABLE 1
Number of Warning and Guidance Systems, Categorized by Channel and Level of Control

Task		Warning		Guidance	
Level of Control*	Type	Input controls	Seat(belt)	Input controls	Seat(belt)
Strategic	Navigation	2	2	-	-
	Eco-friendly **	1	-	4	-
Manoeuvring	Speed limit **	6	1	2	-
	Blind spot	1	2	3	-
	Collision avoidance	3	2	2	-
Control	Car following	4	8	5	-
	Curve negotiation	-	-	7	-
	Lane keeping	12	4	15	-

Channel: The component that is used to communicate the haptic signal to the driver.
Input controls: Steering wheel, gas pedal or joystick.
Seat(belt): Seat, seatbelt, torso belt, and biceps/wrist straps.
*As proposed by Donges [85] and Michon [86].
**Eco-friendly driving and obeying the speed limit are difficult to categorize according to the levels of control by Donges [85] and Michon [86]. Both these tasks are executed at the control level. Obeying the speed limit is considered to be planned at the manoeuvring level, whereas eco-friendly driving has a large strategic component.

the warning device (i.e., the cry-wolf phenomenon) [80], whereas a late warning may have a negative effect on safety because the driver has too little time to react.

The second type of system is the guidance system. Guidance systems are defined as systems that:

- continuously support the driver when the system is activated;
- provide a feedback signal that assists the driver to make an appropriate action; and
- provide feedback the intensity of which is dependent on an external variable that represents the vehicle position on the road (e.g., deviation from road centre) or relative to another vehicle (e.g., THW).

Guidance systems are designed to support the driver by exerting forces on a control interface. A guiding force communicates both the direction and the magnitude of the recommended action. For example, in Hart [82] a counterforce dependent on the THW and time to collision (TTC) relative to a lead car was exerted on the gas pedal. Guidance systems are sometimes described by a metaphor of horse and rider [38]. One of the advantages of guidance systems, as reported by Abbink et al. [39], is that loss of situational awareness and skills is mitigated because the driver is continuously involved in the vehicle control loop. However, De Winter and Dodou [83] argued that there are also several potential safety issues concerning guidance systems, such as after-effects when the system is disengaged. Petermeijer et al. [84] showed that there is a trade-off between benefits (i.e., improved performance) and limitations (i.e., detrimental after-effects) when drivers are supported by guidance systems.

b) Supported task. Warning and guidance systems have been used to support various types of tasks. The tasks were categorized into three levels of control as originally proposed by Donges [85] (see also Michon [86]): (1) strategic, (2) manoeuvring, and (3) control tasks (see Table 1).

Strategic level. Tasks at the strategic level are tasks that "define the general planning stage of a trip" [86]. Our review showed that warning systems have been applied to two types of strategic tasks: navigation and eco-friendly driving. The navigation task requires the driver to search for directional signals and interpret them, after which he/she has to decide to take a turn or make a lane change. Three studies were found in which haptic feedback systems were used to support navigation [7], [24], [71]. Van Erp and Van Veen [7] used vibrations on the left/right side of the seat to indicate which way the driver should turn at the next inter-section. Ege et al. [71] tested four (spatial and temporal) haptic warning signals that informed the driver to turn left or right at an intersection and to approach or leave a roundabout. Hogema et al. [24] used an 8 x 8 matrix of vibration motors in the seat pan to indicate eight possible directions: the four cardinal and four oblique directions.

Eco-friendly driving has the goal of improving fuel economy and reducing the carbon footprint. The philosophy here is to avoid large pedal depressions and large accelerations of the vehicle. Five studies [8], [34], [35], [36], [44] investigated systems that support eco-friendly driving. Birrel et al. [44] investigated a warning system that vibrated the gas pedal when the driver depressed the gas pedal more than 50 percent. In Jamson et al. [35] (see also [8], [34], [36]) a guidance system provided a counterforce on the gas pedal when it was depressed too much.

Manoeuvring level. Collision avoidance, obeying the speed limit, and performing a blind spot check are tasks at the manoeuvring level. Haptic feedback systems are primarily used for collision avoidance and the evasion of stationary obstacles [21], [23], [27], [43] or pedestrians [28], [61]. In one study [41] a haptic guidance supported not only longitudinal control but also lateral control in order to avoid collisions with stationary obstacles.

When drivers make a lane change, overtake a lead vehicle, or take a turn, they have to check the blind spot of the vehicle to ensure no vehicles are present. Blind spot checking is not a continuous task, but a safety check before executing a heading change. We found three studies that used a haptic system to support the blind spot check [58], [63], [64].

Seven studies [17], [23], [25], [26], [27], [38], [68] supported the driver in obeying the speed limit.

Control level. We found 41 studies that supported a task at the control level, namely curve negotiation, lane keeping, or car-following [5], [6], [10], [11], [12], [14], [15], [19], [20], [30], [31], [32], [33], [37], [39], [40], [42], [45], [46], [47], [48], [49], [50], [51], [52], [55], [56], [57], [59], [60], [62], [65], [66], [67], [69], [70], [74], [76], [77], [78].

Car following is a task in which the driver keeps a safe and consistent headway to a lead car. Fifteen studies [6], [10], [14], [22], [30], [33], [37], [39], [40], [42], [45], [51], [59], [60], [74] were found that used a haptic system to support the driver in car-following.

Curve negotiation and lane keeping are both tasks aimed at keeping the vehicle within the limits of the road or lane. Although the goal of these tasks is the same (i.e., driving within boundaries), the execution is somewhat different. In lane keeping the driver's goal is to stay in the centre of the lane, whereas with curve negotiation drivers normally tend to 'cut the corner' on the inside [46].

In three studies, one haptic system provided force feedback to support the driver in two tasks simultaneously. Specifically, Brandt et al. [41] combined lane keeping with obstacle avoidance, Flemisch et al. [38] combined lane keeping with obeying the speed limit, and Adell et al. [27] combined collision avoidance with obeying speed limit.

c) Channel. The channels that were most frequently used by haptic support systems were the steering wheel [5], [11], [12], [15], [19], [20], [28], [29], [32], [37], [41], [42], [43], [46], [47], [48], [49], [50], [55], [56], [57], [64], [65], [66], [67], [69], [70], [72], [73], [75], [77], gas pedal [6], [17], [22], [23], [25], [26], [27], [34], [35], [36], [40], [44], [45], [68], [71], [74], seat [7], [21], [31], [51], [52], [63], and seatbelt [27], [37], [60], [64]. Two studies used a combination of channels, namely Racine et al. [58] (steering wheel & gas pedal) and Adell et al. [27] (gas pedal & seatbelt). Other studies used a joystick [38], [54], biceps straps [61], waist belt [14], [30], [59], or wrist bands [76].

All 38 guidance systems used the input controls as channel, whereas none used the seat or seatbelt. Most haptic warning systems used vibration motors that were in direct contact with the driver at a particular location on his/her body. Typical examples are vibrations applied on the steering wheel or seat pan.

d) Signal. Table 2 shows the number of systems per function and feedback type. Most warning systems used vibrations, whereas almost all guidance systems used forces to communicate with the driver. There are 6 studies [17], [18], [23], [25], [26], [27] in which an active gas pedal provided a counterforce when the driver exceeded the speed limit. In the present literature survey such a system is considered a warning system, since the strength of the force feedback was not dependent on an external variable relative to the position on the road or other vehicles. One guidance system [78] used vibrations to assist the driver in his lane keeping task. The vibrations were continuously provided on the steering wheel and changed intensity as a function of the lateral deviation of the car. Larger deviations resulted in stronger vibrations.

TABLE 2
Number of Warning and Guidance Systems that Used Vibrations or Force as Feedback

	Vibrations	Force
Warning	42	6
Guidance	1*	37

*In Onimaru and Kitazaki [78] vibrations were continuously provided to the driver on the left or right of the steering wheel, indicating the recommended steering direction. The intensity of the vibrations corresponded to the lateral error with respect to the lane centre.

Most vibrators exerted vibrations with a small sinusoidal amplitude and a frequency between 5 and 290 Hz [5], [7], [11], [14], [21], [22], [27], [29], [30], [31], [37], [38], [41], [42], [43], [44], [59], [60], [61], [62], [63], [64], [74], [75], [76].

In addition to the sinusoidal vibratory signals at a single location there are two alternatives. First, several systems have used multiple vibration devices to achieve spatial vibratory patterns. These systems vary from two separate vibrators on the left and right of a steering wheel to a two dimensional matrix of multiple vibrators located in a seat [7], [24], [42], [63], [71]. Second, several studies have used asymmetric vibrations in order to provide drivers with a direction cue. These asymmetric vibrations were used to communicate the haptic signal through the steering wheel, a concept called "motor priming" by Navarro et al. [5], [11], [31], "action suggestion" by Hoc et al. [15], or "pulse-like steering torque" by Suzuki et al. [29] and Huang et al. [57]. In this article we will refer to these systems as motor priming. The philosophy behind motor priming is that when a driver leaves the road, the system will vibrate with asymmetric amplitudes. The difference in amplitude intuitively indicates which direction to steer the car. For the sake of simplicity, motor priming systems will be considered a warning system in the remainder of this article, even though they are a hybrid form between guidance and warning systems.

All but one study investigating guidance systems used forces to communicate with the driver (Table 2). In most studies the force exerted by the system was either a function of an external variable that represented the current position of the vehicle with respect to the road (e.g., deviation from lane centre) [6], [27], [32], [38], [39], [45], [46], [58], [65], [66], [67], [68] or used a look-ahead principle, which determined the future position of the vehicle with respect to the road (e.g., time to line crossing) [12], [30], [41], [47], [48], [49], [54], [55], [56], [67], [69]. Guidance systems designed to support car-following often used a function that combined TTC and THW to determine a counterforce on the gas pedal [6], [22], [39], [45]. Some systems used a more elaborate function to determine the feedback force, for example De Winter et al. [40], who used a two-dimensional weighting function to calculate the force on the gas pedal, Itoh et al. [28], who used an elaborate function that predicted the future pedestrian position to guide an avoidance manoeuvre, and Brandt et al. [41],

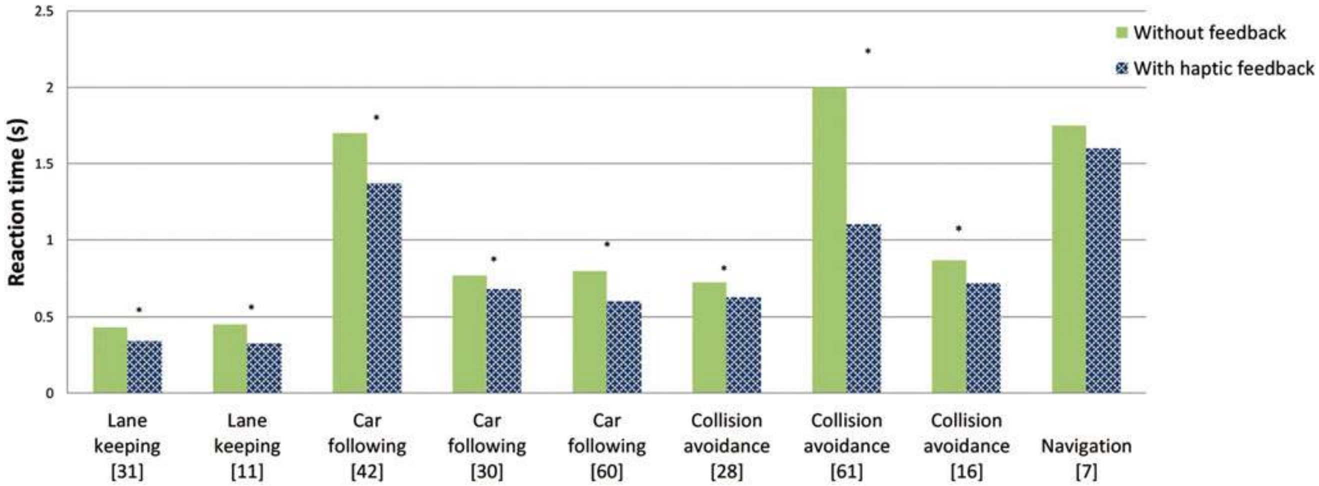

Fig. 1. The results concerning the reaction time of drivers comparing without haptic feedback to haptic feedback provided by a warning system. In most studies, reaction time is the time between the onset of the warning signal and the moment the participant reacted to this signal. Statistically significant differences ($p < 0.05$) are indicated by an asterisk. For all but one study [35], the numeric values were extracted from figures. For [16], the mean across different vibrations patterns was calculated.

who evaluated a concept that created a "hazard map" to guide the driver towards the safest area.

3.3.2 Effects of Haptic Systems on Driver Performance

a) Evaluation measures. The most commonly used measures for evaluating haptic warning systems are (1) reaction time [7], [14], [21], [24], [27], [28], [29], [30], [33], [37], [52], [53], [57], [59], [60], [61], [62], [74], [76] and (2) time to return to a normal situation (e.g., return time to safety envelope) [5], [11], [15], [31], [52], [57]. In most studies, reaction time was defined as the time between the onset of the haptic warning and the moment the participant reacted to this signal, for example by applying the brakes. Other dependent measures that were used for warning systems were the number of collisions, the number of lane excursions, and the number of warnings received.

Guidance systems were often evaluated by means of a performance measure describing how well a task is executed by the participant [6], [12], [34], [35], [36], [39], [42], [45], [46], [47], [49], [50], [55], [56], [65], [66], [69], [70]. The dependent measures used to evaluate performance differ across studies, but are usually related to accuracy or precision (e.g., root mean squared error of lane centre error).

Other frequently used measures were physical workload (e.g., measured by, for example, mean exerted torque on the steering wheel), mental workload (measured by the NASA Task Load Index [TLX] or secondary task performance such as scores on a signal detection task), control activity (measured, for example, by steering wheel reversal rate or the mean and standard deviation of the steering wheel angle), and visual demand (measured by a visual occlusion method).

b) Results of the studies. Eight out of nine studies reported a significant decrease in reaction time when a haptic support system was used compared to no warnings (see Fig. 1) [11], [16], [28], [30], [31], [42], [60], [61], [70]. Van Erp and Van Veen [7] found no statistically significant difference between haptic warning and no warning for a navigational task.

Two studies investigated visual versus haptic signals: Ho et al. [14] found no significant difference in reaction time for a secondary task between haptic and visual cues, and Scott et al. [60] found a significantly faster reaction time for haptic cues. However, when comparing auditory to haptic cues most studies did not find a significant difference [31], [51], [59], [60], except of Stanley [52] and Murata et al. [70] who found a significant difference in favour of the haptic modality.

Three studies [5], [11], [31] showed that combining haptic with auditory warnings does not significantly change the reaction time compared to haptic warnings only. However, Lee et al. [51] found longer reaction times for haptic compared to multimodal (i.e., haptic combined with auditory) feedback. Yet, Ege et al. [71] found that haptic and auditory cues combined were more effective (i.e., fewer navigational errors) than auditory cues alone.

The effectiveness of haptic warning systems seems to be greatly affected by the content (i.e., frequency and amplitude) of the signal. Jensen et al. [43] provided a vibration of the steering wheel to warn the driver of an obstacle in the lane ahead. They showed that participants hit fewer obstacles for a higher frequency and amplitude of the signal. Navarro et al. [5], [11], [31] showed that motor priming yielded shorter "return-to-lane times" than symmetric vibrations, yet Hoc et al. [15] found for the same evaluation measure no statistically significant difference, and Suzuki et al. [29] observed that uninstructed participants sometimes steered their vehicle in the wrong direction. In the latter study, participants reported that the motor priming felt like a lateral disturbance (e.g., wind gust). On the other hand, Huang et al. [57] showed with instructed and trained participants that wrong steering action did not occur. Haptic warnings have also been shown to yield a decrease in the number of collisions with a lead vehicle compared to no [21], [37], [42], auditory [59], and visual [14] warnings. Three studies [30], [60], [70] compared no, auditory, and haptic warnings, but none found a significant difference in reaction time between the modalities. None of the studies that compared no warning to a haptic warning showed a difference in the number of collisions between conditions.

When the multiple vibration components are spatially separated from each other, it is possible to provide directional cues to the driver. Straughn et al. [61] distinguished between compatible (indicating the correct response of direction) and incompatible (indicating the direction of an obstacle or situation to be avoided) cues. There is no consensus regarding which of these two types of cues is more effective to warn a driver. Straughn et al. [61] suggested that warnings should be compatible in case of late warnings and incompatible in case of early warnings, but Beruscha et al. [62] suggested that incompatible mapping is preferred for in-vehicle applications.

Although directional warning systems often do not distinguish between more than two directions, that is, left/right or front/back, there are studies that evaluated more spatially and temporally complex haptic warning patterns [7], [21], [71]. Fitch et al. [21] found that when participants had to distinguish between more than three patterns, the reaction time increased significantly.

In general, studies evaluating guidance systems showed positive results as compared to non-aided driving. Fourteen studies showed an improvement in performance [12], [32], [38], [39], [41], [45], [46], [47], [50], [54], [65], [66], [67], [69]. Table 3 shows the performance measures that the studies evaluating haptic guidance compared to manual control. All but two studies of systems supporting lane keeping or curve negotiation showed a statistically significant improvement in performance. However, the results for systems supporting car-following were inconclusive, with two of the four car-following studies [39], [40] showing no improvement in performance.

Four studies reported a decrease of control activity [6], [12], [45], [46], and two more studies reported a decrease in visual demand, measured with a visual occlusion method [65], [66]. Mulder et al. [6], Griffiths et al. [66], and Flemisch et al. [38] showed, using a secondary task, a decrease in mental workload, but Steele et al. [65] reported no significant difference in mental workload (measured with a mental arithmetic task) between no and haptic feedback. Collectively, the available results suggest that the guidance systems are effective in decreasing the mental workload of the driver.

According to Flemisch et al. [38], systems with a higher level of haptic assistance result in lower mental workload. Likewise, Mulder et al. [12], Mohellebi et al. [50], Toffin et al. [32], and Brandt et al. [41] showed a performance improvement for increasing levels of haptic assistance.

Nonetheless, four studies showed an increase in the driver's physical effort [12], [45], [46], [47], as measured by the forces exerted on the gas pedal or steering wheel. Adell et al. [23] showed an increase of physical demand and effort using the NASA-TLX self-reported questionnaire [87]. Várhelyi and Mäkinen [26] reported a similar increase in physical demand and effort for a haptic gas pedal, although this effect was not statistically significant compared to a no-assistance condition.

Two studies [48], [66] found that guidance systems supporting lane keeping resulted in more crashes with obstacles compared to a no guidance condition, when these obstacles were placed in the centre of the lane, because the guidance did not recognize these obstacles. Conversely, Brandt et al. [41] showed a decrease in collisions when combining guidance and warning systems into a single haptic system.

4 Discussion

4.1 System Design

In our literature survey, we showed that a clear distinction can be made between warning and guidance systems. The design of guidance and warning systems differ in three fundamental ways. First, guidance systems provide continuous support, whereas warning system activate upon exceeding a threshold [11]. Second, guidance systems typically use forces (low frequency, large amplitude) that are not only informative but that may also directly influence the control input [54], whereas warning systems use vibrations (high frequency, small amplitude). Third, guidance systems use the control input devices as a feedback channel, whereas warning systems can also be communicated via, for example, the seat or seatbelt.

For most studies, the evaluated system could be easily classified as either a warning or a guidance system. There were some exceptions, however. Navarro et al. [5], [11], [31] investigated a motor priming concept that suggested the direction of a steering action by exerting asymmetric vibrations of the steering wheel, placing this concept somewhere in between guidance and warning systems. The small amplitude of vibrations do not make it like an actual guidance force, but the asymmetric vibrations do make it different from a traditional warning system. Navarro et al. [5] considered motor priming "as a driving assistance at the boundary between LDWS and LKAS".

Most systems that were evaluated in this article relied on a simple control algorithm. Yet, elaborate algorithms exist as well. For example, a haptic system can combine warning and guidance systems, an approach which was used in a study by Flemisch et al. [38]. In their study, drivers were guided in a lane-keeping task by means of a haptic joystick, and additionally were provided with haptic warnings when crossing the lane boundaries. Indeed, a haptic guidance system could adjust its stiffness/force according to the situation in numerous different ways. Griffiths et al. [66] stated: "A more proactive system would assess the traffic situation and help the driver make an evasive maneuver", a feature that several groups have investigated [12], [28], [41], [47], [72]. The algorithm used by Marchal-Crespo et al. [69] was adaptive and reduced the guidance when the driver improved his/her performance. Abbink et al. [13] argued that a driver will adapt his/her neuromuscular response to match the torque exerted by the controller (i.e., on the gas pedal or steering wheel). Mars et al. [88] suggested that different driving situations (i.e., clear or fog conditions) require a different amount of feedback forces, and argued in favour of a situation-adaptive support system.

4.2 Evaluation Measures

Studies differed widely with respect to their experimental designs and driving environments. A similar observation was made by Nitsch and Farber [89], who performed a meta-analysis on the effects of haptic interfaces on task

TABLE 3
Evaluation Measure, Effect Size, Number of Participants, Experiment Design, and Statistical Significance of Studies Comparing a Guidance System to No Guidance

Performance	Study	Measure	Number / Design*	Result	Significance
Curve negotiation	Mulder 2012 [12]	↓ M $D_{InsideCurve}$ [1]	34/W	$F(1,31) = 24.638$	$p < 0.001$
		↓ SD $e_{Lateral}$ [2]		$F(1,31) = 38.531$	$p < 0.001$
		↓ Max $e_{Lateral}$ [2]		$F(1,31) = 60.731$	$p < 0.001$
		~ M $TLC_{Left/Right}$ [3]		-	Not sign.
	Mulder 2008 [46]	↓ RMS $e_{Lateral}$ [2]	12/W	$F(1,11) = 24.683$	$p < 0.01$
		↑ Min TLC_{Left} [3]		$F(1,11) = 46.200$	$p < 0.01$
		↑ Min TLC_{Right} [3]		$F(1,11) = 16.569$	$p < 0.01$
	Steele 2001 [65]	↓ M $e_{Lateral}$ [2]	22/W	-	$p < 0.0001$
	Mohellebi 2009 [50]	↓ SD $e_{RelativeHeading}$ [4]	12/W	$F(2,22) = 9.52$	$p < 0.001$
		↓ SD $e_{Lateral}$ [2]		$F(2,22) = 10.91$	$p < 0.0005$
	Profumo 2013 [49]**	~ Min TLC[3]	27/B	-	-
		↑ Min TLC[3]		$F = 37.9$	$p = 4 \times 10^{-8}$
Lane keeping	Forsyth 2006 [67]	↓ MS $e_{Lateral}$ [2]	18/W	$F(2,32) = 4.860$	$p = 0.014$
	Griffiths 2005 [66]	↓ RMS $e_{Lateral}$ [2]	11/W	$F(1,21) = 4.9$	$p = 0.05$
		↓ RMS $e_{Lateral}$ [2]		$F(1,21) = 12$	$p = 0.005$
		↓ RMS $e_{Lateral}$ [2]		$F(1,21) = 8.78$	$p = 0.014$
		↑ % Obstacles hit		$F(1,21) = 9.4$	$p = 0.01$
		~ % Obstacles hit		$F(1,21) = 3.5$	$p = 0.09$ (not sign.)
		~ % Obstacles hit		-	Not sign.
	Marchal-Crespo 2010 [69]	↓ M abs $e_{Lateral}$ [2]	62/B	-	$p < 0.001$
	Brandt 2007 [41]	↓ M $e_{LateralPlanned}$ [5]	16/W	-	Sign.
		↓ % Obstacles hit		-	Sign.
	Tsoi 2010 [47]***	↓ RMS $e_{Lateral}$ [2]	12/W	$F(1,11) = 42.556$	$p < 0.01$
		↓ RMS $e_{Lateral}$ [2]		$F(1,11) = 77.433$	$p < 0.01$
	Katzourakis 2011 [41]	~ % road departures	30/W	-	Not sign.
	Flemisch 2008 [38]	↓ M $e_{Lateral}$ [2]	10/W	-	-
	Blaschke 2009 [17]	↓ Max $e_{Lateral}$ [2]	30/W	$F = 10.086$, df = 4	$p < 0.001$
	Toffin 2007 [28]	↓ RMS $e_{Lateral}$ [2]	5/W	-	-
	Breyer 2010 [20]	↑ M $D_{Laneboundary}$ [1]	29/W	$F(2,50) = 8.56$	$p < 0.01$
		↓ SD $D_{Laneboundary}$ [1]		-	-
	Lee 2014 [73]	~ M $e_{Lateral}$ [2]	40/B	$F(3,36) = 1.00$	$p < 0.4035$ (not sign.)
	Mars [77]	↓*SD* $e_{Lateral}$ [2]	24/B	$F(1,22) = 6.26$	$p < 0.05$
	Kienle 2012 [54]	↓ M $e_{Lateral}$ [2]	18/W	$F(1.4, 23.6) = 72.3$	$p < 0.001$
Car following	Abbink 2011 [39]	~ SD THW[13]	10/W	-	Not sign.
		~ SD iTTC[13]		-	Not sign.
	Seto 2008 [22]	~ 5^{th} percentile THW[12]	12/W	$F(1,11) = 4.20$	$p < 0.07$
		~50^{th} percentile THW[12]		$F(1,11) = 1.12$	$p < 0.31$ (not sign.)

TABLE 3 (Continues)

Control Activity					
Curve negotiation	Mulder 2012 [12]	↓ SSR[6]	34/W	$F(1,31) = 36.180$	$p < 0.001$
		↓ SD $\alpha_{Steering}$[7]		$F(1,31) = 69.582$	$p < 0.001$
		↓ SD $a_{Lateral}$[8]		$F(1,31) = 64.238$	$p < 0.001$
	Mulder 2008 [46]	↓ SRR[6]	12/W	$F(1,11) = 5.629$	$p = 0.037$
		↓ SD $\alpha_{Steering}$[7]		$F(1,11) = 24.897$	$p < 0.01$
	Hoc 2006 [15]	~ M $\alpha_{Steering}$[7]	12/B	$t(10) = 1.84$	$p < 0.095$ (no sign.)
	Profumo 2013 [49]**	~ TTR[9]	27/B	-	-
		↑ TTR[9]		$F = 50.05$	$p = 3 \times 10^{-9}$
Car following	Mulder 2010 [6]	↓ SD α_{Pedal}[10]	9/W	$F(1,8) = 25.439$	$p < 0.01$
	Tsoi 2010 [47]***	~ SD $\alpha_{Steering}$[7]	12/W	-	-
		↓ SRR[6]		$F(1,11) = 27.251$	$p < 0.01$
	De Winter 2008 [40]	~ SD F_{Brake}[11]	12/W	-	No sign.
		~ SD $\alpha_{Steering}$[7]		-	No sign.
		~ M THW[12]		-	No sign.
		~ SD THW[12]		-	No sign.
Visual Demand					
Lane keeping	Steele 2001 [65]	↓ # of key presses	22/W		$p < 0.001$
	Griffiths 2005 [66]	↓ M VisD[14]	11/W	$F(1,21) = 96$	$p = 0.0001$

Measures:

↓ = lower, ↑ = higher, ~ = no statistical difference, M = mean, SD = standard deviation, Max = maximum, Min = minimum, RMS = root mean

[1] Distance to lane boundary at the inside of the curve or lane boundary. [2] Lateral deviation from lane centre. [3] Time to lane crossing calculated using the vehicles lateral velocity and acceleration. [4] Relative heading error between road and vehicle. [5] Lateral deviation from planned trajectory, which steered around obstacles. [6] Steering wheel reversal rate: The number of 2 deg reversals on the steering wheel angle per unit of time. [7] Steering wheel angle. [8] Lateral acceleration. [9] Torque reversal rate: The number of directional changes, above a certain threshold, per second of the measured torque. [10] Gas pedal depression angle. [11] Brake pedal force (N). [12] Time headway (m). [13] Inverse time to collision. [14] VisD (visual demand): VisD = 1.0/($t_i - t_{i-1}$), with t_i = time of the i^{th} key press.

Studies:

** Number of participants / Within (W) or Between (B) subject design.*

*** Profumo 2013 [49] performed an experiment with normal and low visibility.*

**** Tsoi 2005 [47] performed a study investigating two haptic feedback algorithms LCAeasy and LCAhard.*

performance with teleoperation systems. They stated: "This heterogeneity in findings also reflects the impression one gains when viewing the literature: that a wide disparity in methods, tasks and systems exists, which are difficult to unite under broader themes".

The results of two studies suggest that faster steering reaction times lead to lower lane excursion times [52] and a lower number of collisions with objects [60]. In contrast, Navarro et al. [11], [31] showed that motor priming yielded faster return-to-lane times while participants had the same reaction times as vibratory warnings. They stated that "the increase of steering wheel peak acceleration, which reflect the sharpness of drivers responses, appears to be the main factor in that process" [31]. We use these results to argue that reaction time is not always an indicator of a system's effectiveness, and statements based on reaction time results alone should be interpreted with caution. An alternative could be to measure higher-level behavioural effects, such as gaze behaviour, situation awareness, and vigilance. Recarte and Nunes [90], for example, investigated the mental workload of a driver by evaluating their gaze behaviour in unsupported driving. This type of paradigm could also be used to evaluate support systems.

Another approach to investigate high-level behavioural effects could be to measure driver responses at a neuromuscular level, which can indicate to what extent drivers agree with the guidance forces. Abbink et al. [39] showed that drivers adapt the end-point admittance (i.e. "the causal dynamic relationship between the force acting on the limb (input) and the position of the limb (output)") of their arms depending on the task instruction (give way to the forces, resist the forces, or relax), indicating that the cognitive state of a driver has a large influence at the neuromuscular level. Moreover, Abbink et al. [39] showed that drivers' admittance increases when using a haptic guidance system, indicating that they do not resist guidance but give way to it. This can be an effective way to infer a disagreement between driver and guidance [13].

4.3 Driving Performance

In general, it can be concluded that a warning or guidance system provides benefits for the driver in terms of an improved performance, reduced reaction time, and reduced mental workload.

4.3.1 Warning Systems

The results of the studies that measured reaction times to haptic warnings showed a clear effect, namely a decrease of reaction time for haptic feedback compared to no feedback. However, the effect sizes were not consistent between the experiments (Fig. 1). Similar results were found in a meta-analysis by Prewett et al. [91], namely that vibrotactile cues enhance performance when added to a baseline task and that effect sizes varies across tasks. The inconsistency in effect sizes in our survey seems largely attributable to differences in measurement methods. For example, Straughn et al. [61] defined reaction time as the time between the moment that TTC dropped below a 4.0 s threshold until a steering input, whereas Gray et al. [16] defined reaction time as the time between the moment that TTC dropped below 3.0 s and a braking input.

Two studies [5], [29] suggest that, after receiving a directional (auditory or spatially separated haptic) warning, the driver will assess the situation visually before acting, effectively reducing the directional cue to a non-directional warning signal. On the other hand, haptic directional cueing has been proven effective in non-driving tasks, such as hovering a helicopter [92]. Meng and Spence [93] argued that static vibrotactile feedback is effective as a warning, while dynamic vibrotactile patterns may be a promising method to present directional cues to a driver. Likewise, Spence and Ho [94] stated that multisensory warnings capture the driver's attention more effectively than unimodal feedback.

Humans have difficulty distinguishing between haptic signals that are presented in close spatial or temporal proximity. Fitch et al. [21] showed that interpreting more than three different patterns degraded the effectiveness of the system. They stated: "Despite the intuitive layout of the haptic seat display, determining the meaning of multiple haptic seat alerts consumes cognitive resources which may implicate their utility". Jones and Sarter [95] emphasized that more research is needed concerning vibrotactile arrays and preferred stimulation locations as a function of the supported task.

The effectiveness of motor priming is still under a lot of debate. Several motor priming studies [5], [11], [31], [57] showed positive results, whereas Suzuki and Jansson [29] reported that drivers perceived motor priming as intrusive wind gusts and steered the wrong way. Navarro et al. [11] hypothesized that motor priming is beneficial because it provides directional cues on a motor level instead of a higher cognitive level. The discord between results for motor priming suggests that there is a small bandwidth of signal content where the signal efficiently operates on the motor level. That is, signals that use very high amplitudes will be perceived as intrusive and may trigger incorrect behaviour, and low amplitudes will probably reduce the effectiveness or have no effect at all.

In summary, the effectiveness of a warning system seems to be affected by a variety of design parameters, including the activation threshold and signal content. As Enriquez et al. [96] stated "by varying the content of the haptic signal (location, waveform, duration, intensity, amplitude, frequency) the haptic signal can aid the user in identifying the message being conveyed".

In actual on-road applications, drivers may turn off the system when they consider the warning signal to be intrusive or annoying [81]. Whether a signal is considered annoying or not is not only dependent on the signal content but also on the activation threshold. Early warning systems, for example, allow the driver to assess the situation before taking action, but will also probably result in false alarms [80].

4.3.2 Guidance Systems

The effectiveness of a guidance system is, just as a warning system is, dependent on design parameters. The algorithm of a guidance system can be a function of many variables, for example the external variable that is used (e.g., THW and/or TTC), as well as the relation between the external variable used and the exerted guidance force (e.g., linear or quadratic).

The degree to which the goals of the driver and system agree with each other has an important influence on the effectiveness of a guidance system. Most existing guidance systems attempt to optimize an external variable (e.g., to minimize deviations from the lane centre [66] or predicted lateral deviation [12], [47]). Boer [97] argued that drivers show satisficing instead of optimizing behaviour, meaning that they are not aiming to minimize deviations always and everywhere. This could lead to several challenges in the design of haptic guidance systems. First, similar to warning systems, if the guidance system is considered intrusive or annoying because it keeps guiding while the driver deems the situation safe (for example when a driver cuts a corner), the driver may turn it off. Second, when the driver and system have different goals (e.g., the driver wants to overtake while the system wants to keep the car at the lane centre), the disagreement could even lead to unsafe situations. Griffiths and Gillespie [66] showed that such disagreement could lead to collisions with obstacles in the middle of the road when drivers are supported by a lane-keeping system. However, innovative methods have been developed to support lane changes [47] and avoid such problems.

4.3.3 Detrimental Long-Term Effects

Several studies have shown that haptic guidance decreases the mental workload and visual demands of the driver. These effects are stronger for haptic guidance systems that provide a higher level of haptic authority [84]. Consequently, haptic guidance could possibly have a negative influence on the vigilance of the driver [98]. Petermeijer et al. [84] showed, by incorporating an automation failure at the end of the experiment, that adverse after-effects can be an issue.

De Winter and Dodou [83] suggested that complacency and skill degradation are topics that should be investigated in future research. Guidance and warning systems might also evoke behavioural adaptation. That is, when the driver feels comfortable with the system, he/she may adopt faster driving speeds or shorter headways.

Four long-term studies [17], [23], [26] (warning systems; test period between one and eleven months) and [69] (guidance system, retention after one week) were found, but these studies were not specifically focused on long-term automation issues, such as skill loss, complacency, automation bias, and behavioural adaptation. Two studies [17], [18] focused on the behavioural adapation of the driver (i.e., changes in mean speed). These studies showed that participants drove with lower mean speeds when the warning system was active, and that there was no behavioural adaption (in terms of mean speed) when the participants used the system over long periods of time (between five and eleven months). Mars et al. [77] did not find "any evidence of global behavioural adaptation" in a study that investigated a lane-keeping system that provided forces on the steering wheel.

5 Conclusion and Recommendations

The present survey evaluated 70 empirical studies on haptic assistance in driving. The results indicate that warning systems mainly use vibrations as the communication signal, whereas guidance systems typically use continuous force feedback. The studies investigating warning systems mostly use reaction time measures, while the studies investigating guidance systems typically use vehicle-centred performance measures such as the mean and standard deviation of a longitudinal and/or lateral driving variation. Providing haptic feedback to the driver offers short-term benefits in terms of improved performance, reduced reaction times, and reduced mental workload.

In order to reduce necessary heterogeneity in research findings, we support ongoing efforts to standardize definitions, performance measures, and research methods in driver behaviour research, like Östlund et al. [99]. Regarding guidance systems, adaptive algorithms are a research topic that deserves to be investigated, whereas for warning systems dynamic temporal and spatial patterns are of interest. Finally, almost all haptic driver support system research focused on short-term evaluations. Whether the short-term effects will last in the longer term, as well as long-term automation issues and behavioural adaptation need to be investigated in future studies.

Most of the studies included in this survey investigated the haptic systems in 'ideal' conditions, that is, short sessions in which the driver was probably attentive and the system was working perfectly. A more thorough investigation of the situations where either the driver or the system does not operate optimally is recommended.

We have no doubt that in the far future it will be possible for cars to drive fully automatically. However, there will be a number of difficult human factors, societal, and legal obstacles to be overcome before such systems can truly be introduced on the roads. We agree with Michon [4] who suggested already in the 1990s that human-machine cooperation is a means to overcome the gap until wholly automated driving becomes technically feasible.

Acknowledgments

The authors wish to thank Dimitra Dodou for her comments during the final stages of this work. Sebastiaan M. Petermeijer and Joost C. F. de Winter are involved in the European Marie Curie ITN project HFAuto—Human Factors of Automated driving (PITN–GA–2013–605817).

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