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Title:

Haptic foot pedal: influence of shoe type, age, and gender on subjective pulse perception

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50 words abstract:

This study investigates the influence of shoe type (sneakers and safety boots), age and gender on the perception of haptic pulse feedback provided by a prototype accelerator pedal in a running stationary vehicle. Drivers within three age groups ("≤ 39", "40-59" and "≥ 60") took part.

Biographies:

Claudia Geitner:

Claudia Geitner graduated in Media-Computer-Science at the Dresden University of Technology (Germany). The major subject and major research interest was Human-Computer Interaction. She then proceeded to work in the field of Human Factors in the areas of web design and power plant design. Claudia is currently an Engineering Doctorate candidate at the University of Warwick (UK) researching into how drivers interact with new in-vehicle technology and effects of that interaction on the driving behaviour.

Stewart Birrell:

Stewart A. Birrell has a BSc (Hons) degree in Sport Science from the University of Hertfordshire and a PhD in Ergonomics from Loughborough University. His primary research interests concern how humans interact with their surroundings and subsequent effect on task outcome and performance, which has been developed through working within a variety of different domains such as sport, military and transport. Stewart has recent experience in the design and evaluation of in-vehicle systems, where currently he works as an Assistant Professor at University of Warwick investigating human factors aspects of low carbon transport. Stewart has numerous scientific papers published in the field of Human Factors.

Claudia Krehl:

Claudia Krehl obtained her PhD 2014 at the University of Nottingham, investigating how Human Computer Interaction for Mobile Devices can be improved in multitasking situations with multimodal and context aware interface designs. Currently, Claudia works as Senior Human Factors Engineer at Jaguar Land Rover.

Paul Jennings:

Professor Paul Jennings is the lead academic for the '3xD Simulator for Intelligent Vehicles, the world's first immersive, simulated environment for smart and connected vehicles. He is Deputy Chief Technology Officer of the University of Warwick's centre High Value Manufacturing Catapult, and has worked for over 25 years on collaborative automotive research, leading projects funded by the Engineering and Physical Sciences Research Council, Innovate UK and the EU, valued at over £20m. He pioneered the use of interactive sound evaluation in the automotive industry through a vehicle simulator now exploited globally by Bruel and Kjaer.

Haptic foot pedal: influence of shoe type, age, and gender on subjective pulse perception

Short title: Factors affecting haptic pulse perception on a foot pedal.

Abstract: This study investigates the influence of shoe type (sneakers and safety boots), age and gender on the perception of haptic pulse feedback provided by a prototype accelerator pedal in a running stationary vehicle. Drivers within three age groups ("≤ 39", "40-59" and "≥ 60") took part.

Objective: This study investigates the influence of shoe type (sneakers and safety boots), age and gender on the perception of haptic pulse feedback provided by a prototype accelerator pedal in a running stationary vehicle.

Background: Haptic feedback can be a less distracting alternative to traditionally visual and auditory in-vehicle feedback. However, to be effective the device delivering the haptic feedback needs to be in contact with the person. Factors, such as shoe type, vary naturally over the season and could render feedback that is perceived well in one situation, unnoticeable in another. In this study, we evaluate factors that can influence the subjective perception of haptic feedback in a stationary but running car: shoe type, age, and gender.

Method: Thirty-six drivers within three age groups ("≤ 39", "40-59" and "≥ 60") took part. For each haptic feedback, participants rated intensity, urgency and comfort via a questionnaire.

Results: The perception of the haptic feedback is significantly influenced by the interaction between the pulse's duration and force amplitude, and by the participant's age and gender, but not shoe type.

Conclusion: The results indicate that it is important to consider different age groups and gender in the evaluation of haptic feedback. Future research might also look into approaches to adapt haptic feedback to the individual driver's preferences.

Application: Findings from this study can be applied to the design of an accelerator pedal in a car, e.g. for a non-visual in-vehicle warning, but also to plan user studies with a haptic pedal in general.

Keywords: tactile interaction, haptic perception, driver assistance system

INTRODUCTION

Haptic feedback can be an alternative to visual and auditory in-vehicle feedback, interfering less with the primarily visual-cognitive task of driving. Previous studies demonstrated that haptic feedback, such as vibration or counterforce, can reduce the driver's workload when presented while the driver interacts with non-driving relevant information, e.g. the in-vehicle infotainment system (Lee, Hoffman, and Hayes, 2004; Brown, 2005; Birrell, Young, and Weldon, 2013). Adell, Várhelyi, and Hjälmdahl (2008) even identified a haptic pedal with counterforce as a preferred solution for warnings when speeding, compared to an acoustic and visual warning. To be effective, users need to perceive the haptic feedback as clearly noticeable, but still comfortable (Abbink, 2006). In this study, we evaluate how factors that vary naturally within users influence the subjective perception of haptic feedback: shoe type, age, and gender.

Drivers perceive haptic feedback from a pedal via their shoe. A driver's footwear can vary notably over the year. So far, the shoe type was rarely subject of evaluations. Abbink and Van der Helm (2004) and Ichinose, Gomikawa, and Suzuki (2013) evaluated the just noticeable perception of haptic pulses, varied in force amplitude and frequency, on the foot via the shoe. Participants wearing shoes with stiff soles needed comparable greater force amplitudes to perceive the pulse. The difference in perception between the shoe types appears to decrease as the pulses become more noticeable. More research is needed to understand if the influence of shoe type reduces as pulse noticeability increases, and that if these increase in either amplitude, force or duration mean that the feedback is still perceived as comfortable by the user.

Shoe types might influence the perception of haptic feedback particularly in older drivers. Whereas previous driving related studies related to haptic pedal interfaces included mainly young participants (De Rosario et al., 2010; Ichinose et al., 2013; Abbink and Van der Helm, 2004), other research has shown that physical perception of haptic feedback appears to decline with age (Inglis, Kennedy, Wells, and Chua, 2002; Brown, 2005; Perry, 2006; Shaffer and Harrison, 2007). Perry (2006) found that older participants were less sensitive to vibrations of greater than 100 Hz. Early research by Verrillo (1982) came to a similar conclusion, comparing the perception of 25 and 250 Hz on the hand. The results emphasize the need to consider older people when evaluating the perception of in-vehicle haptic feedback to ensure its noticeability.

Feedback presented to the driver should be balanced between being easy to notice, but not startling. Startling feedback can increase the drivers' reaction time (Biondi, Rossi, Gastaldi, and Mulatti, 2014). This balance is not easy to achieve. For example, literature suggests differences in haptic perception, specifically that of comfort, between gender. Females seem to be more sensitive to pressure on the skin (Hale and Stanney, 2004) and to vibration (Hennig and Sterzing, 2009). However, literature varies, Hennig and Sterzing (2009) did not find a gender-related difference in the perception of touch and Schlee (2010) did not discover a gender-related perceptual threshold difference in vibration. An explanation could be that sensitivity decreases with age, but more so for males compared to females (Halonen, 1986; Hilz, Axelrod, Hermann, Haertl, Duetsch, and Neundörfer, 1998). This study evaluated gender as a potential influence on the perception of intensity and comfort of a haptic feedback.

This study assessed a single haptic pulse that can be envisioned as a bump, comparable to a tap with the finger. In this study the haptic pulse was modified by force amplitude (intensity of the touch) and duration. Preliminary findings were presented in Geitner, Birrell, Skrypchuk, Krehl, and Jennings (2015), with this current paper extending the analysis and recommendations to include all pulse settings evaluated as well as further considering the effects of age and gender.

To the authors' knowledge, there is no study evaluating the combined effects of shoe type (sneakers and safety boots), age, and gender on the subjective perception of haptic pulse feedback from a pedal in a car. They are evaluated together in this study. As literature suggests, all three variables could influence haptic perception.

MATERIALS AND METHOD

This study assessed the influence of shoe type, age and gender on the subjective perception of haptic pulses. It is hypothesized that:

- Shoes with a thicker and stiffer sole influence the perception of haptic pulses negatively, but only for just noticeable pulse feedback
- Age has a negative influence on the perception of haptic pulses.
- Females are expected to perceive the intensity of haptic feedback stronger than males.

Participants

Thirty-six people took part and were included in the analysis of the data. Normal haptic perception and no known illness affecting haptic perception, such as diabetes (Travieso and Lederman, 2007), were prerequisites for participation in this study.

To test the hypothesis, participants were distributed across three age groups and both genders, similar to that used by Mehler, Reimer, and Coughlin (2011) to evaluate physiological workload measures.

Table 1. Overview of the participants in the study.

	Age "≤ 39" years		**Age "40 – 59" years**		**Age "≥ 60" years**	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
Number of participants	6	5	8	5	7	5
All participants in an age group	11		13		12	

The University of Warwick's Biomedical and Scientific Research Ethics Committee approved the study (REGO-2014-1312).

Apparatus

Equipment. The study was conducted in a stationary but running Range Rover vehicle with an implemented proprietary haptic pedal prototype (Figure 1). According to the hypothesis, two shoe types were evaluated: shoes with a thick and stiff sole (safety boots) and shoes with a thin and flexible sole (sneakers). The shoes were provided to the participant to avoid unwanted variations. Beforehand, a set of shoe sizes (sizes 5 to 10) had been estimated that would cover 95% of the population. The participants wore their own socks in the shoes. Both shoe types were comparable in weight. Soles were approximately 8 millimeter (mm) for the sneakers and 14 mm for the safety boots.

Figure 1. Study equipment.

Selection of pulses. Pulse settings in this study were presented by force amplitude in Newton (N), and duration in milliseconds (ms). One pulse can be considered as a single vibration. A pulse’s duration can then be expressed as frequency. The term duration is used throughout this study. Frequency (in Hertz (Hz)) is mentioned additionally for comparison with related literature that applied frequency in Hz. The pulses were presented as sine-shaped waveform (Figure 2). Activation of the feedback required the pedal to be depressed. During a pulse, the pedal moved upwards in the set parameters, adjusted by a software.

The pulse settings were selected in a range from just noticeable to clearly noticeable, constrained by the prototype haptic pedal implemented in the car. The force amplitude was adjustable from 6-21 N and the duration from 2 s to 16 ms (0.5 - 62.5 Hz). Following findings from Abbink and Van der Helm (2004) and Ichinose et al. (2013), 9 N / 1 s was selected as just noticeable feedback and 7 N / 1 s as just below the noticeable feedback for shoes with thin and flexible soles (1 s = 1 Hz for a single pulse). The highest amplitude was 18 N, selected after a pilot in which pulses with greater amplitudes were perceived as either uncomfortable or too strong. The durations 67, 33, and 20 ms were selected to cover the spectrum available by the haptic pedal prototype. Table 2 lists all pulse settings selected for this study.

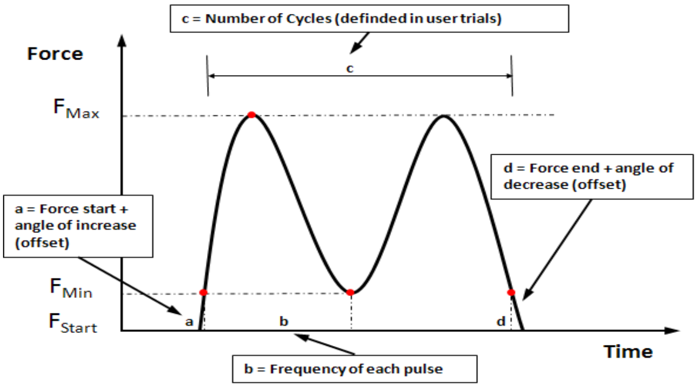

Figure 2. Pulse in sine-shaped waveform.

Table 2. Sixteen pulses were employed in this study; Top - Force amplitudes in Newton (N), Middle - Duration of the pulse expressed as frequency in Hertz (Hz), and Bottom - Duration of the pulse in milliseconds (ms).

7 N	9 N	14 N	18 N	7 N	9 N	14 N	18 N	7 N	9 N	14 N	18 N	7 N	9 N	14 N	18 N
1 Hz	1 Hz	1 Hz	1 Hz	15 Hz	15 Hz	15 Hz	15 Hz	30 Hz	30 Hz	30 Hz	30 Hz	50 Hz	50 Hz	50 Hz	50 Hz
1000 ms	1000 ms	1000 ms	1000 ms	67 ms	67 ms	67 ms	67 ms	33 ms	33 ms	33 ms	33 ms	20 ms	20 ms	20 ms	20 ms

Experimental environment. Literature and pilot studies indicated that haptic perception varies over the sole of the foot (Inglis et al., 2002; Kennedy and Inglis, 2002). The heel and toe region seem to be more sensitive than ball and arch. Also, joints, tendons and muscles are activated when the leg moves (e.g. depressing the pedal) and contribute to the haptic perception (Hale and Stanney, 2004). They could result in different perception of a haptic pulse presented on the foot dependent on seating position and movement of the leg. Those considerations led to the following experimental settings to control for extraneous variables:

- *Position of the seat:* The participants were required to adjust the seat to a position suitable for driving, where they could comfortably reach the pedals and steering wheel.

- *Position of the foot on the pedal:* To ensure a comparable equal contact between the foot and pedal, participants were instructed to use their whole foot on the pedal. Additionally, they were instructed to keep the heel on the ground, making it easier to hold the pedal in a stable position. Some participants who had difficulty reaching the pedal just kept their whole foot on the pedal as priority.

- *Pedal angle:* To ensure a consistent pedal angle (and subsequent force which needed to be applied) haptic feedback commenced when the vehicle's RPM (revolutions per minute of the engine) was stable at between 1,500 and 2,000 RPM. Using this RPM setting helped ensure the haptic feedback was presented when the pedal travel was minimal.
- *Vibrations of the car itself:* The study was conducted in a static but running car to increase realism (e.g. with vibration of the engine) and applicability of results. The background vibration was kept stable through the applied controlled range of RPM.
- *Temperature in the cabin:* Temperature in the cabin was controlled at a comfortable range for the participant.

Questionnaire for perception of the haptic feedback

The participants rated each haptic pulse with three questions concerning intensity, comfort and urgency (how much a pulse motivates reaction) (Table 3). Abbink's (2006) suggestion, to balance comfort and clear perception of haptic feedback, resulted in two questions about comfort and intensity of perception in this study. Uncomfortable feedback carries the risk to startle the driver, which would increase the reaction time, and is adverse for a warning related to safe driving. Employing urgency as a dimension can help in the development of an incremental warning including warnings that trigger a faster reaction from the driver. Therefore, a question addressing urgency was added. Comfort and urgency were rated on a seven-point rating scale similar to Brown (2005). Intensity was rated on a five-point rating scale as found in (Kaaresoja and Linjama, 2005).

Table 3. Subjective ratings for each pulse.

(1) Was the feedback perceived?

1	**2**	**3**	**4**	**5**
Not detected	Weak	Moderate	Strong	Too strong

(2) How comfortable was the feedback?

1	**2**	**3**	**4**	**5**	**6**	**7**
Not comfortable						Very comfortable

(3) How urgent did the feedback feel? (if participants feel they should react to the feedback)

1	**2**	**3**	**4**	**5**	**6**	**7**
Not urgent						Very urgent

Procedure

The participants were introduced to the study, signed an institutional consent form, and adjusted the seat to a position they would take for driving and started the car. Before the start of the study they familiarized themselves with the haptic pedal. They depressed the pedal and when a stable position of the pedal was found (e.g., between 1,500 and 2,000 RPM), the experimenter presented two varying example pulses (not part of the set, e.g., 10 N / 50 ms). The participants practiced rating their perception by answering three questions after the perception of each pulse (Table 3).

The participants experienced either sneakers or safety boots first, in a counterbalanced order across age and gender. The set of sixteen pulses (Table 2) was randomized six times. Three of those randomized sets were presented to the participants in the first shoe condition and the other three in the second shoe condition. The experimenter initiated a pulse when the participant kept the foot in a stable position on the pedal, between 1,500 and 2,000 RPM. After perceiving one pulse, the participant rated this pulse in (1) intensity, (2) comfort, and (3) urgency (Table 3), always in that order. For an efficient and consistent procedure during the study, participants were advised to keep the foot on the pedal and the pedal depressed during one set of sixteen pulses. Abbink and Van der Helm (2004) mentioned that participants applied varying rating strategies for the perception of the pulses. This variation was one of the reasons which led to a repeated measure design in this study. The study lasted approximately one hour per participant.

Data Analysis

The data analysis was conducted in R (R Core Team, 2014). Pulses that were not detected by the participants were rated as 1 in intensity (“Not detected”), and no urgency and comfort rating were recorded. The ratings for intensity, and comfort were interpreted with parametric statistics. Each participant perceived and rated each pulse six times (three times in each shoe condition), each time for intensity, comfort, and urgency. The three repeated ratings for (each) intensity, urgency and comfort for a pulse in one shoe condition were aggregated into a mean rating, to reach a comparably balanced rating with the participant adjusting to the rating scales during the repeated representation of pulses.

Mean comfort ratings were widely distributed with a standard deviation (SD) ranging from 1.35 to 1.6 (on a 7-point rating scale). It might have resulted from different rating strategies. Some participants took the middle of the scale as baseline, whereas others rated comfort high unless they felt uncomfortable with their foot. To take the individual strategies into account, a new comfort classification was generated referred to as "balanced comfort" (BC). Balanced comfort was calculated by the z-score formula. By applying the formula the individual mean rating for a participant are considered and the comfort rating could be compared along its standard deviation to that mean. First, the mean comfort rating over all pulses (p) and shoe conditions (s) was calculated for each participant. Then this mean comfort rating over all pulses (μ) for a participant was subtracted from the specific participant's comfort rating for the current pulse ($c_{s,p}$). Last, the subtraction was divided by the standard deviation of the participant's comfort ratings (σ). The further analysis was based on these balanced comfort ratings. This balancing technique was only employed for the comfort ratings as these ratings had the highest variance and visually different rating patterns.

$$BC = (c_{s,p} - \mu) / \sigma \mid 1 \leq s \leq 6, 1 \leq p \leq 16$$

In the descriptive presentation, intensity and urgency ratings appeared to follow a similar pattern. Therefore, a two tailed Pearson Product Correlation test was conducted. The result suggests a strong positive correlation between intensity and urgency ratings, $r(2904) = .81$, $p < .001$. Due to the strong correlation of the urgency and intensity ratings, the analysis for the urgency ratings is not presented in more detail.

An ANOVA analysis was conducted to evaluate effects of shoe, age and gender on the ratings of intensity of the haptic pulses, each with a critical value of $p < 0.05$. The ANOVA included an error calculation for the within subject variables (shoe, force amplitude and duration). The analysis considers main effects of age, gender, and shoe type only. The sample size would be too small to return a suitable power for analyzing potential effects between age groups, if we split by gender. Comfort ratings were analyzed with t-tests, due to the reduced number of comfort ratings when pulses were not perceived.

RESULTS

The data set was tested for homogeneity of variance with the Levene test and met that criterion. Then an omnibus mixed model ANOVA analysis was conducted to evaluate the intensity ratings. The model included perception as an independent variable and age, gender, shoe, duration and force amplitude as dependent variables. The model included an error correction for the within subject variables shoe, duration, and force amplitude. Its results suggested interaction effects of duration, force amplitude, gender and age on the perception of the pulses. The influence of gender ($F(1,30) = 5.05$, $p = 0.03$), force amplitude ($F(3,90) = 496.66$, $p < .001$) and duration ($F(3,90) = 253.09$, $p < .001$) is significant overall. The effects of the between subject variables age and gender were analyzed in detail with the Tukey HSD.

Experience of the Pulses Overall

The variability of the ratings over all the pulses were as follows: standard deviations (SDs) between 0.42-0.82 for intensity, SDs between 0.98-1.45 for urgency and SDs between 0.53-1.37 for balanced comfort. Over all pulse settings, force amplitude and duration of the pulses were rated significantly different, indicating the participants perceived them as different ($F(9,270) = 206.36$, $p < .001$). Duration seemed to be the main influence on perception of the haptic pulse feedback, giving it a characteristic.

The data examined across each combination of force amplitude and varying durations can be described by different perceptual patterns, grouped either by duration (Figure 3) or by force amplitude. The intensity rating for a pulse of a certain duration increased with larger force amplitude. Intensity ratings for durations of 1000 ms rose steeply with higher force amplitudes, from just detectable in combination with the lowest force amplitude (7 N) to strong in combination with 18 N. Similarly, intensity ratings for 67 ms pulses increased with stronger force amplitudes to a mean intensity rating between moderate and strong (rating 3-4). The intensity ratings for pulses with a duration of 33 ms increased only slightly with higher force amplitude. Pulses of the shortest duration of 20 ms were an exception from that pattern. They were rated hard to perceive independent from the combined force amplitude. In addition, over all pulses, 7 N was rated as just perceivable or weak in this study. Pulses with a force amplitude of 7 N also included the highest percentage of not perceived pulses (rated as “not detected”).

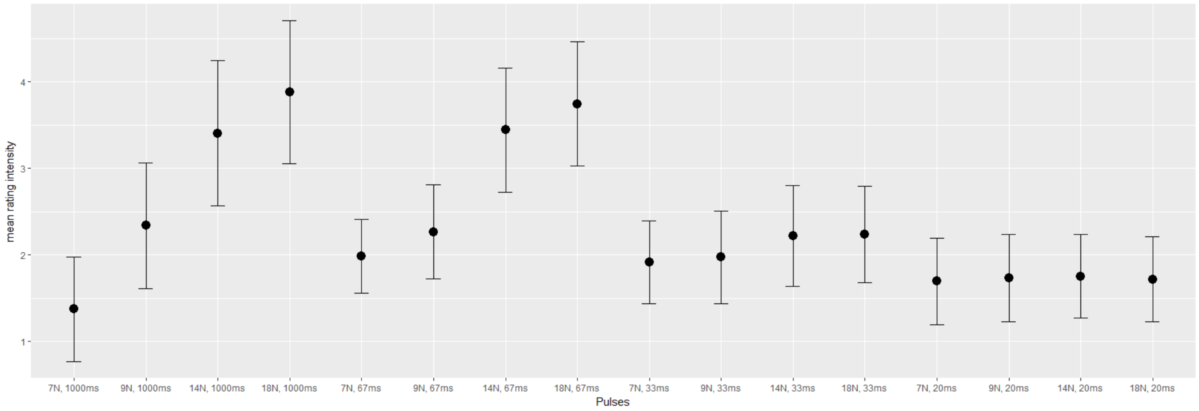

Figure 3. Mean ratings for intensity calculated over all participants and both shoe conditions (the rating scale in Table 3, question (1)). The mean intensity rating is presented for all sixteen pulses sorted by duration.

Ratings for balanced comfort showed an inverse pattern to intensity ratings, increasing from pulses rated high in intensity to being highest for pulses rated as weak in intensity. Pulses rated as “too strong” in intensity tended to receive a negative comfort rating (Table 3). Given the rating scale selected, an optimal rating for pulse intensity could be considered between 3 (moderate) and 4 (strong). A rating of 5 states “too strong” on the rating scale indicating a negative bias, a potential to startle the driver. The negative bias of an intensity rating of 5 is supported by participant’s negative comfort rating.

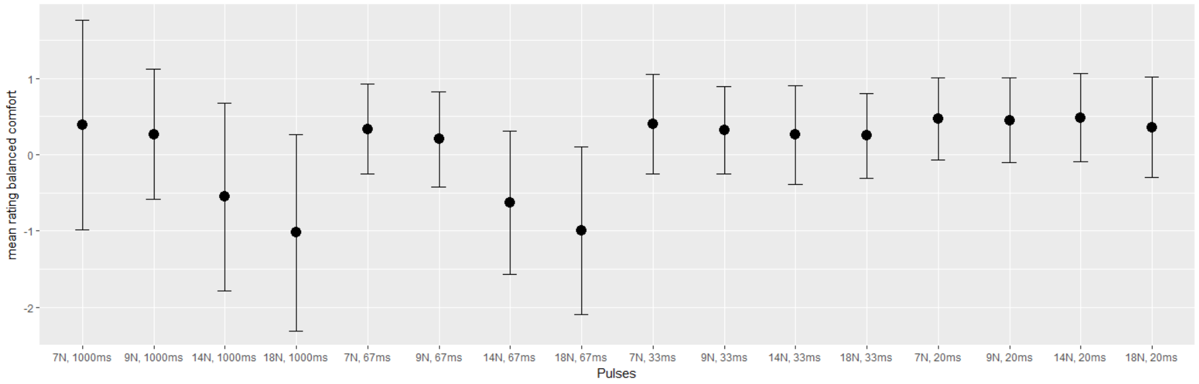

Figure 4. Mean ratings for balanced comfort for all pulses (not comfortable – negative, neutral – 0, comfortable – positive).

Effect of Shoe Type on Perception

In contrast to the previous study by Abbink and Van der Helm (2004), intensity ratings in this study did not differ significantly between the two shoe conditions, $F(1,30) = 0.28$, $p = 0.6$. There were no significant interactions between shoe type and the other variables of the ANOVA model. Potential reasons, such as the more realistic study design, are described in the Section “Discussion and Conclusion”. Due to the non-significant result, no post-hoc analysis was conducted.

Effect of Age on Perception

In the overall repeated measure ANOVA analysis age itself appeared not to have a significant effect alone on the intensity of the pulses (*F*(1,30) = 0.04, *p* = 0.95). However, the omnibus ANOVA analysis showed significant interaction effects between age and force amplitude (*F*(6,90) = 2.39, *p* = 0.03); between age and duration, (*F*(6,90) = 2.45, *p* = 0.03); and between age, duration, and gender, (*F*(6,90) = 2.77, *p* = 0.01). A post-hoc analysis with Tukey HSD revealed that the youngest age group (≤ 39) and the oldest age group (≥ 60) rated the short duration pulses of 20 ms (*p* = 0.03) and 33 ms (*p* = 0.006) significantly different in intensity.

***Table 4*.** Overview of mean ratings for intensity and balanced comfort compared across age groups (the percentage of missed pulses was calculated with respect to the number of ratings in the specific age group, because the age groups are not equally distributed).

		Pulse feedback settings: Force Amplitude in Newton (N) and duration in millisecond (ms)															
		7N	9N	14N	18N	7N	9N	14N	18N	7N	9N	14N	18N	7N	9N	14N	18N
		1000 ms	1000 ms	1000 ms	1000 ms	67 ms	67 ms	67 ms	67 ms	33 ms	33 ms	33 ms	33 ms	20 ms	20 ms	20 ms	20 ms
age group "≤ 39"	Mean rating for intensity	1.46	2.36	3.24	3.91	1.95	2.20	3.35	3.67	2.03	2.09	2.3	2.38	1.73	1.83	1.74	1.79
	Percentage of missed pulses	57.6%	4.5%	3%	0	13.6%	4.5%	0	0	7.6%	7.6%	6.1%	0	31.8%	22.7%	27.3%	21.2%
	Mean rating bal. comfort	0.68	0.18	-0.81	-1.1	0.35	0.29	-0.67	-1.05	0.5	0.38	0.29	0.32	0.4	0.43	0.43	0.37
age group "40-59"	Mean rating for intensity	1.37	2.32	3.36	3.71	2.01	2.31	3.4	3.67	1.91	1.99	2.19	2.15	1.77	1.76	1.82	1.77
	Percentage of missed pulses	70.5%	5.1%	1.3%	1.3%	5.1%	1.3%	0	0	15.4%	16.7%	7.7%	9%	24.4%	27%	21.8%	27%
	Mean rating bal. comfort	0.02	0.35	-0.41	-0.95	0.35	0.1	-0.57	-0.92	0.29	0.27	0.26	0.16	0.4	0.46	0.45	0.3
age group "≥ 60"	Mean rating for intensity	1.27	2.33	3.61	4.03	1.98	2.28	3.58	3.9	1.81	1.85	2.17	2.19	1.58	1.61	1.68	1.6
	Percentage of missed pulses	77.8%	15.3%	0	0	11%	4.2%	0	0	25%	20.8%	5.6%	5.6%	41.7%	38.9%	33%	41.7%
	Mean rating bal. comfort	0.41	0.27	-0.48	-0.99	0.31	0.23	-0.67	-1.03	0.42	0.31	0.23	0.28	0.64	0.45	0.59	0.43

Coding for Table 4

Mean intensity rating:	*dark grey: ≤2 (hardly noticeable)*	*medium grey: >2 & ≤3 (weak)*	*white: >3 & ≤4 (moderate)*	*light grey: >4 (strong)*
Percentage of missed pulses:	*dark grey: >20%*	*medium grey: >5 & ≤20%*	*white: 0*	*light grey: ≤5%*
Mean rating bal. comfort:	*dark grey: ≤-1*	*medium grey: >-1 & ≤0*	*white: >0 or 0*	

Table 4 provides an overview of the participants' intensity and comfort ratings, and percentage of missed pulses for each evaluated force amplitude and duration combination for all three age groups. The shades of grey mark levels of intensity, percentage of missed pulses, and levels of balanced comfort. Pulses with longer durations were rated in average higher in intensity and a smaller number of pulses was missed, in all age groups (lighter shade). Over all pulses, the oldest age group missed a higher percentage of pulses compared to the other age groups (darker shade). Pulses that were rated high in intensity (18 N / 1000 ms, 14 N / 67 ms and 18 N / 67 ms) tended to be rated as less comfortable (darker shade).

Differences in the mean intensity ratings for each pulse between the age groups were calculated in order to further evaluate the influence of age on pulse intensity. Figure 5 shows the calculated difference between the age groups “≤ 39“ and “≥ 60“ as a black dot for each pulse and the 95% confidence intervals as a black bar. A positive difference in the short duration pulses indicated higher intensity ratings by the youngest age group. As the range of the confidence intervals was mostly positive for the short duration pulses (33 ms and 20 ms), this supports the assumption that shorter duration pulses are easier to perceive for the younger age group compared to the oldest age group.

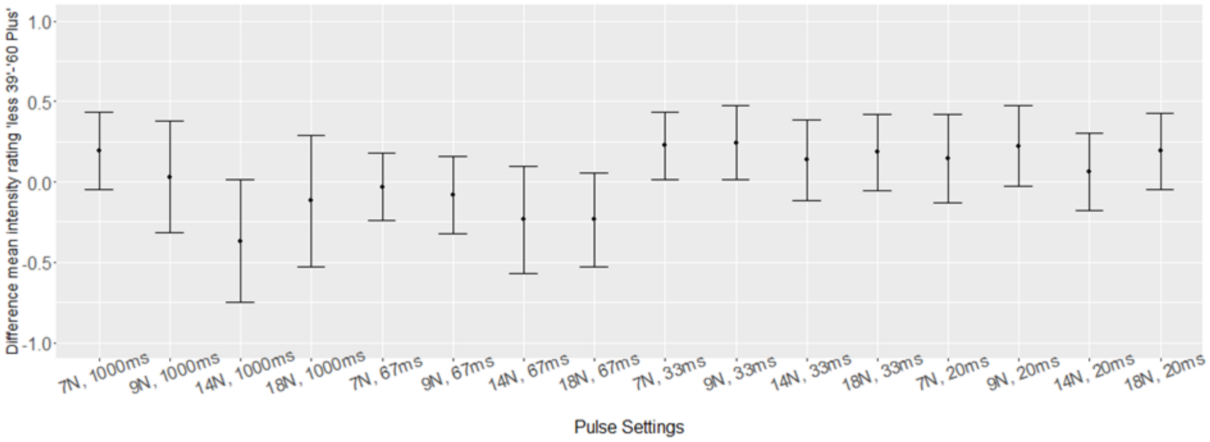

Figure 5. Difference in mean ratings for intensity (youngest age group “≤ 39” minus oldest age group “≥ 60”).

Effect of Gender on Perception

Table 5 provides an overview of the participants’ intensity and comfort ratings for each evaluated force amplitude and duration combination across gender. The shades of grey mark levels of perceived intensity, percentage of missed pulses, and ratings for comfort. Overall, female and male participants rated the intensity of the haptic pulses significantly different ($F(1,18) = 5.05$, $p = 0.03$). Females gave a higher intensity rating and missed less pulses compared to males in all pulse settings (Table 5). However, females tended to rate a pulse that was rated high in intensity on average as less comfortable compared to males, specifically durations of 1000 ms combined with the force amplitudes of 14 and 18 N. Females ($M = 0.51$) perceived shorted duration pulses as significantly more comfortable compared to male participants ($M = 0.38$), $t(171.62) = 2.0$, $p = 0.04$. Females ($M = -0.59$) also rated longest duration pulses as significantly more negative compared to males (*M* = -0.09), $t(232.7) = -3.64$, $p = 0.0003$.

Table 5. Overview of mean ratings for intensity and balanced comfort compared across genders (the percentage of missed pulses is calculated with respect to the number of ratings in the specific gender, because gender is not equally distributed).

		Pulse feedback settings: Force Amplitude in Newton (N) and duration in millisecond (ms)															
		7N 1000 ms	9N 1000 ms	14N 1000 ms	18N 1000 ms	7N 67 ms	9N 67 ms	14N 67 ms	18N 67 ms	7N 33 ms	9N 33 ms	14N 33 ms	18N 33 ms	7N 20 ms	9N 20 ms	14N 20 ms	18N 20 ms
female	Mean rating intensity	1.42	2.63	3.68	4.22	2.04	2.34	3.59	3.92	2.03	2.09	2.31	2.29	1.79	1.87	1.89	1.8
	Percentage of missed pulses	64.3%	3.3%	3.3%	1.1%	5.5%	3.3%	0	0	5.5%	5.5%	3.3%	1.1%	24.4%	18.8%	14.4%	21.1%
	Mean rating bal. comfort	0.2	0.11	-0.98	-1.5	0.46	0.28	-0.75	-1.04	0.5	0.48	0.43	0.37	0.46	0.47	0.55	0.55
male	Mean rating intensity	1.33	2.12	3.21	3.63	1.94	2.21	3.34	3.61	1.83	1.89	2.15	2.2	1.63	1.63	1.65	1.66
	Percentage of missed pulses	72.2%	11.9%	0	0	12.6%	3.1%	0	0	23.8%	22.2%	8.7%	7.9%	38.1%	37.3%	36.5%	36.5%
	Mean rating bal. comfort	0.57	0.39	-0.26	-0.68	0.24	0.14	-0.54	-0.96	0.32	0.18	0.13	0.16	0.47	0.43	0.42	0.19

Coding for Table 5

Mean intensity rating:	*dark grey: ≤2 (hardly noticeable)*	*medium grey: >2 & ≤3 (weak)*	*white: >3 & ≤4 (moderate)*	*light grey: >4 (strong)*
Percentage of missed pulses:	*dark grey: >20%*	*medium grey: >5 & ≤20%*	*white: 0*	*light grey: ≤5%*
Mean rating bal. comfort:	*dark grey: ≤-1*	*medium grey: >-1 & ≤0*	*white: >0 or 0*	

A comparison of the difference in the mean intensity ratings between males and females (mean intensity rating male minus mean intensity rating female) also suggests a tendency for females to rate pulses higher in intensity compared to males. The 95% confidence interval for the calculated difference is mostly negative meaning females rated haptic pulses on average higher than the males (Figure 6).

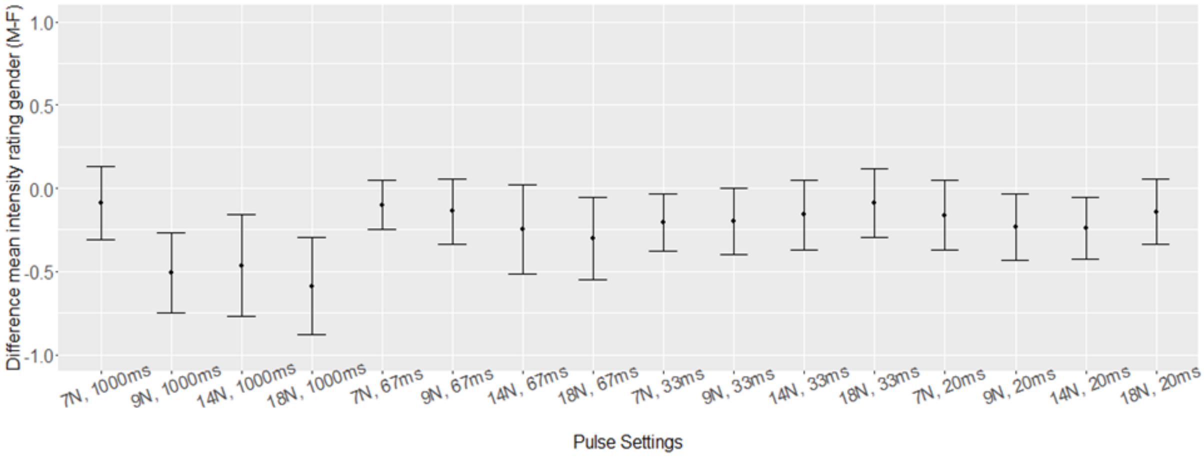

Figure 6. Difference in mean ratings for intensity (Males (M) minus Females (F)).

The difference between male and female ratings remains when the ratings were divided by age group. For the shortest duration it appeared males in the oldest age group rated intensity on average lower compared to females in this age group and participants of other age groups.

DISCUSSION AND CONCLUSION

A mixed model ANOVA analysis conducted over all variables indicates interaction effects between gender, force amplitude, duration and age on the perception of haptic pulses. In contrast to the hypothesis and previous research by Abbink and Van der Helm (20004) shoe type did not have a significant effect on the perception of haptic pulses in this study. The differences in results are possibly due to differences in the design of the studies. In the present study, there was no counter pressure imposed on the foot which could have decreased the perceived intensity. Also, the more realistic design utilizing a stationary running car added a constant slight vibration. Those factors could have reduced the perception of the just noticeable pulses and therewith eliminated slight differences in shoe types. Other findings from this study are in accordance with previous findings from Abbink and Van der Helm (2004): pulses were perceived more often with a higher force amplitude, except for the shortest duration of 20 ms, and an increasing frequency made lower force amplitudes more perceptible, except for the lowest force amplitude of 7 N.

As hypothesized, age seems to affect the perception of haptic pulses, but only in combination with duration. The oldest age group rated the two shortest durations (20 and 33 ms) in average lower in intensity than the two other age groups. Supporting this result, Verillo (1982) has reported a decline of haptic perception with age previously. He found that the sensitivity for vibrations over 25 Hz declined in older participants compared to younger.

Overall, gender had a significant effect on the perceived intensity and comfort of the haptic pulses. As hypothesized, females gave a higher mean rating for intensity for all pulses. This finding is supported by Hale and Stanney (2004) who found a higher sensitivity of females in haptic perception of pressure on the skin. Neely, Burström and Johansson (2001) also found females rated intensity and perceived discomfort higher compared to males for vibration on the arm.

Recommendations from the study

Summarizing, the following recommendations are derived from the study’s results:

Duration (frequency) was the main parameter that influenced haptic pulse perception, and gave it a specific characteristic. Similarly, MacLean and Enriquez (2003) found frequency as a major influence to perception of haptic icons, compared to amplitude or waveform. Some participants described short duration pulses as a “knock” (similarly found by Brewster and Brown (2004)) and long duration pulses as a “bump”.

- ***Durations shorter than 33 ms (in this study it was 20 ms) are not recommended, as they were rated weak in intensity and pulses were missed, independent from the applied force amplitude***. In their experiment about haptic perception of vibration on the finger, Kaaresojya and Linjama (2005) found pulses of 12.5 ms as not perceivable and those of 25 ms duration hard to perceive. The results match those found herein, and strengthen recommendations to apply durations longer than 20 ms.

- ***The duration of 67 ms (15 Hz) is recommended considering the intensity and no or few missed pulses across age groups and across gender.*** 67 ms is, according to Schlee (2010), within the optimal perception range of the haptic receptor type Meissner corpuscle in the skin. A clearly perceivable, haptic pulse for both genders is suggested to range from durations of 67 ms to 1000 ms.
- ***Force amplitudes ranging from 9 N to 18 N are recommended as they were clearly perceivable by all age groups for both genders.*** Similarly, as found by (Abbink and Van der Helm, 2004), lower force amplitudes can be perceived better with longer durations. However, 7 N is too low, independent from the combined duration. Force amplitudes stronger than 18 N should be avoided, as increasing intensity of pulses turns from clear perception into a negative effect of startling the driver (Edworthy and Stanton, 1995).

- ***Subjective perception of comfort and perceived intensity of haptic feedback can be influenced by gender***. Females tended to have a higher sensitivity (higher ratings in perception) and rated clear perceivable haptic pulses as less comfortable in this study.

- ***Shorter pulses appear more difficult to detect for older participants compared to younger ones (higher percentage of pulses not perceived).*** The two shortest pulse durations (20 and 33 ms) were the most problematic. A duration of 33 ms should be combined with high amplitudes in order to be noticeable.

- **Settings might be best selected dependent on the use-case.** For an application as a warning it is important that the signal is not missed, comfort is less important. A high noticeable setting with no missed pulses is, for example, 67 ms combined with 18 N or 14 N, but it is perceived as not comfortable. For informative use-cases comfort may be more important, therefore it could occur that the signal is perceived at a repeated presentation. Such a setting would be for example, 67 ms combined with 9 N, it is perceived as comfortable but a few pulses would be missed.
- ***Studies for haptic feedback should select participants counterbalanced over gender, and should involve older participants***.

Future Research

Comparable to driving on-road, engine and air conditioning produce background noise in the cabin. Amongst that, the haptic pedal prototype produces a gentle sound in some settings, e.g. a squeaking sound for the shortest duration pulses. The sound is not assumed to be associated with haptic perception of comfort or urgency, but it could have negatively influenced the rating of intensity in two ways: it could have been used as a memory aid to distinguish the pulses, or it could have been used as a reference scale instead of the haptic sensation. The memory effect is assumed to be compensated by random presentation order and the size of the set (16 different pulses), and six repetitive ratings (each in a different random order) for each pulse. The sound as a reference scale for ratings of intensity cannot be completely ruled out, but the participants were asked to focus on haptic perception, thus given direction. In future, potential sound of the pedal should ideally be masked with white noise played through the cabin loudspeakers.

A follow-up study could proceed to evaluate effects of age on the perception of intensity and comfort further. It could be assessed if perception of intensity declines more in males compared to females. Comfort of the haptic interface should be evaluated over a longer time. It would help to ensure that the haptic feedback does not become annoying for the driver (Van Erp, 2002; Petermeijer, Abbink, Mulder, and De Winter, 2015).

Based on the results of this study, haptic pulse feedback, which was rated as noticeable but still comfortable, could be applied to a specific use-case and tested further on various on-road conditions. A use-case could be a pulse as notification for exceeding a speed limit. Such a study should consider various road surfaces and vehicle speeds to test the robustness of the haptic feedback. Additionally to the herein presented subjective perception of the warning a future study should consider reaction time as a measure and important factor for road safety. Another important consideration is to design the haptic feedback such that it conveys its meaning naturally. As Norman (2002) suggests an ergonomic design should not make the user (driver) think.

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KEY POINTS

- Haptic pulses between 9 N and 18 N with force amplitudes longer than 33 ms were rated highly noticeable. The higher in noticeability a pulse was rated the more uncomfortable it was perceived (across all age groups and genders).
- When female participants rated a pulse high in intensity, they tended to rate this pulse less comfortable compared to male participants.
- The subjective perception of haptic pulses delivered by an accelerator pedal to the foot was not influenced by shoe type, but was significantly influenced by the pulse’s duration and force amplitude, as well as the participant’s age and gender.

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