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A Fuzzy Expert Model of Haptic Perception for Automobile Touch-Screen Displays

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Abstract

Haptic feedback is currently emerging as a feasible solution to cope with the security-related issues of automobile touch-screen displays, and at the same time to improve users satisfaction and quality of use. Therefore, we have developed a fuzzy symbolic model of haptic perception for automobile interfaces in cooperation with an automotive ergonomics expert. The model predicts the induced comfort degree of the haptic effects based on their ergonomic properties, and achieves, on a set of 48 haptic patterns, a global error rate of 14.6% and a compatibility rate of 89.6% with the expert evaluations.

Keywords: Haptic interfaces, expert knowledge, sensory evaluations, linguistic modeling, automotive ergonomics

1. Introduction

During the last years, the electronic equipment market was dominated by the technological developments achieved in the field of *touch-screen devices*. Based on a perpetual growth, the number of touch-sensitive equipments has already surpassed the psychological threshold of 1 billion units [1].

While smartphones and tablets still represent the main components of this growth, the tactile technology has recently expanded to new markets and products. Therefore, a large range of consumer products have already adopted the touch-screen technology, with some notable examples including: information panels, ATMs, digital cameras, remote controllers or hand watches.

To cope with the increasing customers demands, the automotive industry made significant progresses in this direction, and nowadays touch-sensitive screens have already replaced part of the mechanical interfaces in many modern automobiles [2].

Nevertheless, the conservative nature of the automotive industry pushed manufacturers to study the effects of this transition on passengers safety in a driving situation. These concerns are justified by the well-known fact that driver's engagement with in-car systems can interfere with the main driving task, negatively affecting it [3].

While still obeying to this general condition, current automobile touch-screen interfaces present an additional drawback, which is the lack of mechanical feedback from the device. Indeed, current touch-screen interfaces are *passive*, because unlike *mechanical* buttons, the *virtual* buttons on such displays do not actively stimulate the user's tactile sense. In a driving situation, this mechanical passivity adds additional pressure on the user's visual resources, detracting attention from the main driving task, with negative effects on safety [4]. This is corroborated by traffic security studies [5] showing that taking the eyes off the road for a duration longer than 2 seconds can significantly increase the risk of car accidents.

Faced with such clear evidence, car manufacturers latest efforts aimed at making the interaction with touch-screen displays safer for the end-user. As some researchers point out [6, 7], a possible way to achieve this is through an additional *vibratory feedback*, which is to be delivered by the tactile surface directly to the user finger on screen interaction.

Indeed, short vibrational stimuli, delivered when pushing a virtual touch-screen button, carry an important acknowledgment information about the state of the ongoing interaction between the user and the interface. As a consequence of this active stimulation of the tactile sense, user's visual resources are partially relieved. Moreover, since feedback information is now delivered through multiple senses simultaneously (vision and touch), the global cognitive workload can be reduced, according to the *multiple resources theory* [8].

However, while answering most of the aforementioned safety issues, the use of vibrotactile patterns opens a new and relatively unexplored dimension in automobile ergonomic sciences. Stimuli perception, adaptability and, ultimately, induced comfort are all important aspects that need to be tackled by the automotive industry in the near future.

In this regard, the present paper introduces a novel model of vibrotactile perception based on the evaluations of an expert in automotive ergonomics. Using fuzzy logic and privileged expert knowledge, the proposed model explores the connections between the induced comfort of vibrotactile signals

and their evoked sensory parameters, in the context of in-vehicle information systems. Therefore, an ergonomic vision of haptic perception is introduced, with implications in the design and customization of automobile vibratory patterns.

The rest of this paper is organized as follows. In Section 2 we will present a literature overview on the subject of haptic feedback, with a special consideration for those studies dealing with comfort-related issues or automotive ergonomics. Next, in Section 3, the experiments carried out with the aid of an expert are detailed, and the knowledge acquired by questioning the expert is presented. Then, in Section 4, the fuzzy symbolic model of automobile haptic perception is introduced and validated based on the expert knowledge acquired above. Finally, in Section 5, some concluding remarks are drawn.

2. Ergonomic Overview on Haptic Feedback

From a *psychophysical* point of view, the perceptual aspects of vibrotactile stimulation became an important research topic toward the end of the 1960s. During that time, many important contributions, such as the four channels theory [9] and the Stevens power law of tactile vibration [10], were introduced.

However, it was only at the beginning of the 2000s that the first major studies dealing with the *ergonomic* aspects of haptic feedback appeared. This period coincides with the development of the first touch-screen consumer devices and also with the first attempts to enhance their usability via vibrotactile stimulation.

In a pioneering work [11], the authors show that the time spent scrolling a list on a PDA can be reduced by up to 22% when haptic feedback is present. Subsequent investigations, carried out by Brewster [12], show that the accuracy of phrase entering through a virtual keyboard on a touch-screen tablet can be improved by the haptic modality. This resulted both in a lower number of errors and a higher number of text lines entered. In a similar study, Hoggan *et al.* [13] revealed that, when haptic feedback is active, phrase entering on a touch-screen mobile phone was also faster, as compared to the non-haptic modality. Moreover, in the same study, the authors show that haptic feedback has a positive influence on the users mental workload, frustration and subjective performance level.

Therefore, it seems thus that vibrotactile stimulation, i.e. haptic feedback, improves both the usability and the cognitive workload associated with touch-screen interfaces.

Following the important success reported by the use of haptic feedback in general consumer devices, recently, the automotive industry began exploring this modality for their tactile in-vehicle information systems, as a way to improve the safety standards in a driving condition.

Therefore, in [6], the interaction with a tactile in-vehicle information system is studied for two distinct situations: a) using visual feedback only, and b) using bimodal visual-haptic feedback. The experiments were carried out in a driving simulator and required participants to perform a given task on the tactile surface, while engaged in the main driving task. The study reveled that in the second situation, i.e. using a joint visual-haptic feedback, both the duration of an eye glance and the number of eye glances required for a given task are reduced. This resulted in a global reduction of the task completion time, allowing the driver to focus more visual resources on the main driving task.

The above findings are corroborated by different studies on the same topic, which provide further evidence on the benefits of vibrotactile stimulation for automobile touch-screen displays. Therefore, in [14] the authors found that enabling haptic feedback for touch-screen interaction, while engaged in a virtual driving task, reduced the number of mistakes made, as compared to the non-haptic condition. Moreover, in [15], the effect of multi-modal feedback on drivers workload was estimated through a questionnaire. On this subject, the authors showed that the visual-haptic condition helped reduce the average workload score by more than 11% compared to the visual condition alone.

While these studies all assess the benefits of haptic feedback for automobile touch-screen displays, they do not provide explicit information on the *hedonic* aspects of vibrotactile stimulation. Questions like: *"which ergonomic variables most influence in-vehicle vibrotactile perception?"* or *"how to design, based on these variables, a set of pleasant and comfortable haptic stimuli?"* still need to be answered.

In our previous studies [16] the comfort induced by vibrotactile stimuli was investigated from a *mechanical* perspective, using a set of measured variables associated with human skin's mechanoreceptors. The fuzzy model thus obtained proved useful in determining how the different activation degrees of the mechanoreceptors (as a result of the vibrotactile stimulation) influence the perceived comfort of the haptic stimuli.

However, the model in [16] decomposes the notion of vibrotactile comfort onto a set of *technical* variables, e.g. the stimulus energy within a certain frequency bandwidth or the positive velocity of the vibration. These variables are hard to understand by non-technical users and do not clearly reflect ergonomic expert knowledge in the field. This fact limits the explanatory power of the model.

In order to overcome this major drawback, it has been suggested that the comfort degree induced by vibrotactile stimuli should be decomposed onto a set of *sensory parameters*, closely related with the subjective aspects of haptic perception. Therefore, a complete experimental procedure was established with the aim of relating the sensory features of the vibrational signals with the comfort degree they in-

duce. The proposed experimental procedure, along with the vibrotactile signals employed and the apparatus used to generate them, are presented in the following section.

3. Experimental Procedure and Apparatus

The experimental procedure was designed with the aid of an expert in automotive ergonomics having an experience of more than ten years in the field. It took place at the *Interior Controls Research Laboratory*, in the headquarters of the automotive manufacturer *Valeo*, in Annemasse, France.

3.1. Apparatus and Stimuli

In order to generate a wide range of vibrotactile signals, a novel and dedicated experimental device was used in this study. It was developed by the consortium of the MISAC project (*Multi-fonctional Intelligence Surface for Automotive & Aeronautics Cockpits*) with the intent to boost research on vibrotactile stimulation for future touch-screen interfaces installed in cars and airplanes cockpits.

The apparatus consists of a capacitive touch-screen device able to deliver haptic feedback through an array of piezoelectric actuators disposed under the screen layer. Thanks to the original architecture of the actuators, the vibrotactile signals generated cover the frequency range of 20-300 Hz, and can reach acceleration amplitudes of up to 40 G peak-to-peak. The experimental device is connected to a PC which sends to the actuators the appropriate parameters of the haptic effects to be triggered, and which also stores the subjective evaluations of the expert. A complete illustration of the apparatus is shown in Figure 1. The virtual interface of the tactile screen is displayed in Figure 2.

The above experimental device allowed the generation of 48 unique haptic effects, spanning 12 frequencies between 30 Hz and 300 Hz, two durations, i.e. short and long, and two waveforms, i.e. triangle and sine. Given the wide covering of the input parameters, the set of 48 haptic stimuli was considered complete and representative for an automobile haptic touch-screen interface.

3.2. Experimental Procedure

To let the expert assess *both* the sensory parameters of the haptic effects and their induced comfort degree, the experimental procedure was divided into two different stages, corresponding to the two analyses the expert had to perform: a *sensory* evaluation for the parameters of the vibrotactile stimuli followed by a *hedonic* evaluation.

3.2.1. Sensory analysis of the haptic effects

According to his experience in automotive ergonomics, the expert identified the following sensory parameters of the haptic effects as being the

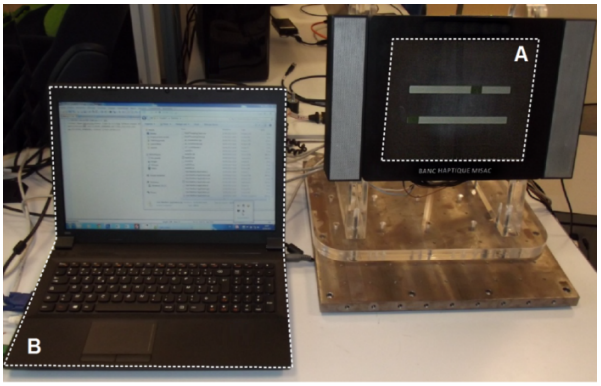
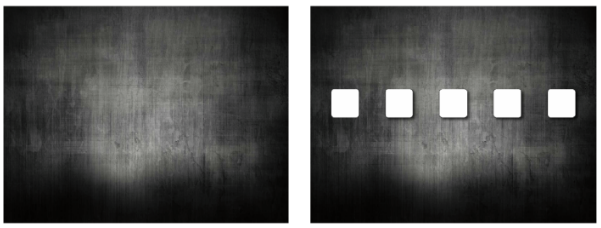


Figure 1: The experimental device used: A) Capacitive touch-screen. The actuators are disposed under the screen. B) The PC communication system.



(a) (b)

Figure 2: Touch-screen virtual interface presenting: (a) the background; (b) a series of five virtual buttons, each associated with an unique haptic effect triggered when the button is pushed.

most relevant ones for automobile touch-screen interfaces:

- *Adaptability of the haptic effect to the automobile driving context*: property assessing whether the haptic effect is well-adapted to be used in automobile touch-screen interfaces; "context adaptability" assimilates several ergonomic characteristics of the haptic effects, such as *intensity*, *stimulus responsiveness* or *perceptual duration*.
- *Neatness*: ergonomic criterion assessing the "perceptual cleanness" of the haptic effect; a *neat* vibrotactile stimulus should be sharp and have no parasite vibrations; otherwise the stimulus would be considered *noisy*.
- *Sensation of displacement*: sensory property used to assess the *perceptual* sensation that the finger "sinks" into the tactile surface as a result of the vibrotactile stimulus received; the "sinking sensation" induced by the haptic effect can therefore create the impression of pushing a mechanical button;

Furthermore, for each of the above properties, the expert proposed several *classes*, as linguistic labels, which can be consulted in Table 1. Therefore, the three properties chosen denote the most salient ergonomic features of the vibrotactile signals. The granularity of each property reflects the expert's dis-

crimination ability, i.e. how many classes of haptic effects can he discriminate for the given criterion.

Therefore, using the apparatus described in Section 3.1, the expert evaluated (by touching the capacitive screen with the fingertip) each of the 48 haptic effects generated, according to the above properties. Hence, for each sensory property, each haptic effect was assigned to one of their corresponding classes. The 48 haptic effects were randomly presented, and the experience was repeated two times. After the two independent runs, the final linguistic label, i.e. class, associated with the haptic effect was considered to be the aggregation of the classes given by the expert in the two runs. Table 2 shows the complete list of possible aggregations for the *Adaptability* parameter. Please note that the "+" operator represents fuzzy sets union, rather that numerical summation [17]. This form of representation allows expert hesitancy to be translated into term graduality, as opposed to forcing an exclusive term. The same methodology was employed for the two other parameters, i.e. *Neatness* and *Displacement*.

Therefore, after the two evaluations we obtain a fuzzy linguistic description for the given haptic effect. Please note that in the rest of the paper, whenever a linguistic label's membership degree is 0, it will be omitted from the description.

The fuzzy linguistic descriptions evaluated by the expert for the three sensory properties, and for each haptic effect, will be later used as input variables for the fuzzy symbolic model of automobile vibrotactile perception.

3.2.2. Hedonic analysis of the haptic effects

The second stage of the experimental procedure consisted in allowing the expert to evaluate the induced *comfort degree* for each haptic effect. Using the same experimental device, the expert evaluated each haptic effect (once again by touching the capacitive screen with the fingertip) and rated the perceived comfort degree induced by the effect. The rates were given on a scale with 5 labels: {*"Very Uncomfortable"*, *"Uncomfortable"*, *"Neutral"*, *"Comfortable"* and *"Very Comfortable"*}. Therefore, each label can be seen as a fuzzy description of the comfort degree.

Moreover, during the experiment, the expert placed himself in a virtual driving situation, and evaluated the *contextual* comfort degree induced by the stimuli. More precisely, according to his expertise, he evaluated the pleasantness of the touchscreen haptic effects, as they would be perceived inside a *running* automobile.

This procedure was repeated three times, allowing to obtain three evaluations on the perceived comfort degree for each haptic effect. The global comfort evaluation was obtained by the same aggregation methodology detailed in Table 2 for the

Criterion	**Classes**
Adaptability	Good
	Acceptable
	Unacceptable
Neatness	Neat
	Average
	Noisy
Sensation of Displacement	Too Much
	Adapted
	Average
	Low
	None

Table 1: Linguistic labels for the sensory criteria defined by the expert.

Adaptability parameter. For instance, if the evaluations given in the three runs of the experiment for haptic effect i, are *Comfortable*, *Neutral* and *Neutral*, respectively, the final comfort evaluation is:

$$Comfort(i) = 0.33/Comfortable + 0.66/Neutral.$$

3.3. Expert Knowledge Rulebase of Vibrotactile Perception

Therefore, each haptic effect is now characterized by the evaluations on the sensory parameters, on the one hand, and by the evaluation on the comfort degree, on the other hand. In order to model expert's knowledge on automobile vibrotactile perception, these two separate knowledge layers must be connected.

Given the fact that the evaluations obtained on the sensory parameters are expressed as fuzzy linguistic descriptions without having a numerical universe of discourse associated, in this study we have chosen a fuzzy symbolic model [18] to link these evaluations to the ones on the induced comfort degree. We recall that a fuzzy symbolic model uses linguistic labels for the input and output variables, but unlike Mamdani systems, the output labels are treated as *symbols*, and not as actual fuzzy subsets.

Therefore, the input variables of the proposed model are the evaluations on the sensory parameters, and the output variable is represented by the evaluations on the comfort degree induced by the haptic effects. The system rule-base was defined together with the expert, and consists of 45 ($3 \times 3 \times 5$) fuzzy "IF-THEN" statements relating the above variables. Due to space limitations, Table 3 presents a collection of only 15 among the 45 rules used.

Please notice that for certain combinations of the antecedents, the system's output, i.e. the perceived

First Evaluation	Second Evaluation	Final Linguistic Label
Good	Good	*1/Good + 0/Acceptable + 0/Unacceptable*
Good	Acceptable	*0.5/Good + 0.5/Acceptable + 0/Unacceptable*
Good	Unacceptable	*0/Good + 1/Acceptable + 0/Unacceptable*
Acceptable	Good	*0.5/Good + 0.5/Acceptable + 0/Unacceptable*
Acceptable	Acceptable	*0/Good + 1/Acceptable + 0/Unacceptable*
Acceptable	Unacceptable	*0/Good + 0.5/Acceptable + 0.5/Unacceptable*
Unacceptable	Good	*0/Good + 1/Acceptable + 0/Unacceptable*
Unacceptable	Acceptable	*0/Good 0.5/Acceptable + 0.5/Unacceptable*
Unacceptable	Unacceptable	*0/Good + 0/Acceptable + 1/Unacceptable*

Table 2: List of possible aggregations for the *Adaptability* parameter.

	Adaptability	Neatness	Displacement	Perceived Comfort
R_1	Good	Neat	Adapted	*1/Very Comfortable*
R_2	Good	Neat	Low	*0.5/Neutral + 0.5/Comfortable*
R_3	Good	Average	Adapted	*1/Comfortable*
R_4	Good	Average	Low	*1/Neutral*
R_5	Good	Noisy	Low	*0.5/Uncomfortable + 0.5/Neutral*
R_6	Acceptable	Neat	Adapted	*0.5/Comfortable + 0.5/Very Comfortable*
R_7	Acceptable	Neat	Low	*1/Neutral*
R_8	Acceptable	Average	Average	*1/Neutral*
R_9	Acceptable	Average	Low	*0.5/Uncomfortable + 0.5/Neutral*
R_{10}	Acceptable	Noisy	None	*1/Uncomfortable*
R_{11}	Unacceptable	Neat	Too Much	*1/Neutral*
R_{12}	Unacceptable	Neat	Low	*1/Uncomfortable*
R_{13}	Unacceptable	Average	Adapted	*1/Neutral*
R_{14}	Unacceptable	Average	None	*1/Very Uncomfortable*
R_{15}	Unacceptable	Noisy	Low	*1/Very Uncomfortable*

Table 3: Expert Knowledge Rulebase of Automobile Vibrotactile Perception.

comfort degree, is given as a fuzzy linguistic description, rather than by a single label, as is the case in R_5 for example. This fact is related to the expert's hesitation on the label to be associated with the given antecedents. However, a sum of the membership degrees equal to 1 was imposed in those cases.

Since the defined rule-base is to be used for further developments of haptic feedback touch-screen interfaces, its consistency must be first validated. For this purpose, in Section 4 the fuzzy symbolic model of vibrotactile perception is detailed, and its quantitative aspects are used to assess the adequacy of the rule-base.

4. Fuzzy Symbolic Model of Vibrotactile Perception

The expert's evaluations on the sensory parameters and those on the perceived comfort degree, along with the fuzzy rules defined, represent the *knowledge base* of the fuzzy symbolic model. The inference between the input space of the sensory properties, to the output space of the perceived comfort degree, is accomplished by the *projection-combination principle* [19].

Since a symbolic model does not automatically guarantee that the sum of the output degrees equals one, special care must be taken in choosing the inference operators, in order to avoid an inferred output of the type "$0.6/Comfortable + 0.4/Neutral + 0.7/Uncomfortable$". Although feasible, these representations are currently considered counter-intuitive by the users. Therefore, in [20] it is shown that a sum of the output degrees equal to 1 can be assured by the *arithmetic product T-norm* as conjunction operator, and the *bounded sum T-conorm* as projection operator:

$$\begin{aligned} \top(a,b) &= a \times b; \\ \bot(a,b) &= min(a+b,1) \end{aligned} \tag{1}$$

Now, let S be a haptic signal with the following

fuzzy linguistic descriptions:

$$Adaptability(S) = 0.5/Good + 0.5/Acceptable$$
$$Neatness(S) = 0.5/Neat + 0.5/Average$$
$$Displacement(S) = 1/Low$$

Using the operators in (1), the rules activated by the above inputs are R_2, R_4, R_7, R_9. Each rule has an activation degree of 0.25, which corresponds to the *product* of the haptic signal inputs. Next, the membership degree for each output symbol is calculated. Below we detail this reasoning for the output symbol *Neutral*.

The *Neutral* symbol can be found in all the activated rules, and in order to compute its global membership degree, we must first compute its partial membership degree in each rule. This gives:

$$Out^{R_2}_{Neutral} = 0.125/Neutral$$
$$Out^{R_4}_{Neutral} = 0.25/Neutral$$
$$Out^{R_7}_{Neutral} = 0.25/Neutral$$
$$Out^{R_9}_{Neutral} = 0.125/Neutral$$

Using the *bounded sum T-conorm*, the final membership degree is:

$$Out_{Neutral} = 0.75/Neutral;$$

Iterating this procedure for each symbol gives the inferred *symbolic* output of the system:

$$Out = 0.125/Comfortable + 0.75/Neutral + 0.125/Uncomfortable$$

In order to validate the consistency of the rule base used, the inferred symbolic output of the system must be compared with the actual output, i.e. the comfort evaluations assessed by the expert. Although some measures based on symbolic distances between the two have been proposed in the literature for this purpose [21], we have decided to defuzzify both outputs and compare them.

Therefore, a set of *modal* or *characteristic* values $M_i \in \Re$ have been assigned to the five output labels in order to obtain a crisp numerical value for the inferred output. This is accomplished using the height method of defuzzification [22], as described below:

$$y = \frac{\sum_{i=1}^{K_{Out}} \mu_{C_i} \cdot M_i}{\sum_{i=1}^{K_{Out}} \mu_{C_i}}$$

where $K_{Out} = 5$ is the number of output symbols and μ_{C_i} is the membership degree of the haptic effect to the output class C_i.

For the fuzzy symbolic model of vibrotactile perception, the modal values assigned to the output symbols {*"Very Uncomfortable"*, *"Uncomfortable"*, *"Neutral"*, *"Comfortable"* and *"Very Comfortable"*} are $\{-2, -1, 0, +1, +2\}$, respectively. The set of modal values was chosen such that it reflects the bipolar nature of the linguistic scale used. Moreover, the equidistant repartition of the modal values indicates that the same perceptual discrepancy was considered between any two adjacent symbols, which seems in agreement with the expert's own knowledge on the matter.

4.1. Experimental Results

Using the evaluations provided by the expert for the set of 48 haptic effects, a *quantitative* analysis of the symbolic model was carried out. The performance indicators used are the Mean Square Error of the system (MSE) and a normalized error measure Δ, defined below:

$$\Delta = \frac{\sum_{i=1}^{M} |P(i) - A(i)|}{\sum_{i=1}^{M} MaxErr_i},$$

with

$$MaxErr_i = \begin{cases} A(i) - min(I_A), \text{if } A(i) \geq k \\ max(I_A) - A(i), \text{otherwise} \end{cases}$$

where M is the number of haptic effects evaluated; P is the array containing the *predicted* comfort values, A is the array containing the *actual* comfort values evaluated by the expert; $MaxErr_i$ is the largest error the system can make when forecasting the comfort value of the haptic effect i; I_A is the interval of variation of the comfort value, i.e. $I_A = [-2, 2]$, and k is its midpoint.

Furthermore, in order to easily detect the incompatibilities between the haptic effects and the fuzzy model, an evaluation tolerance of $U = 0.8$, i.e. 20% of I_A, was used. This value is related to the human evaluation imprecision for vibrotactile stimuli, and was previously agreed with the expert. Therefore, any haptic effect with an absolute difference between its *actual* and *predicted* comfort degrees greater than $U = 0.8$, will be considered incompatible with the model. Let N_{IC} be the number of incompatible haptic effects. Then the *compatibility rate (CR)* of the system is:

$$CR = 1 - \frac{N_{IC}}{M} \ [\%]$$

On the above performance indicators, the results of the fuzzy model for the set of 48 haptic effects are collected in Table 4. A quick analysis of the results reveals that 89.6% of the haptic effects are compatible with the perception model defined, and that the global error of the system is 14.6%. A case-by-case comparison between the predicted and actual comfort values is shown in Figure 3, where the $N_{IC} = 5$ incompatible effects are marked by thick vertical lines. Therefore, for most haptic effects, the model accurately predicts the comfort value, based on their evoked ergonomic properties.

Finally, let us point out that the system global error (Δ) and compatibility rate (CR) are not affected by the actual choice of the modal values, as long as

Indicator	Result
Global Error (Δ)	14.60 %
Compatibility Rate (CR)	89.6 % ($N_{IC} = 5$)
Mean Square Error (MSE)	0.275

Table 4: Results of the Fuzzy Symbolic Model for the Set of 48 Haptic Effects.

they are uniformly spaced. For instance, the same global error and compatibility rate are obtained using the set of modal values $\{-1, -0.5,\ 0, +0.5, +1\}$.

4.2. Discussion

The good quantitative results obtained validate the adequacy of the rule-base used, which can be seen as an ergonomic knowledge base for in-vehicle vibrotactile perception.

A *post-hoc* analysis of the $N_{IC} = 5$ incompatible haptic effects reveals they are not uniformly distributed, but follow a rather specific pattern. Therefore, *three* out of the five incompatible haptic effects have an $Adaptability = 1/Acceptable$ and *one* of them has an $Adaptability = 0.5/Acceptable + 0.5/Unacceptable$. This analysis shows that the model is less accurate in the intermediate sector of the *Adaptability* property, i.e. where the ergonomic adaptability of the haptic effects to the automobile context is in the region of *Acceptable*.

These findings indicate a potential hesitation of the expert for those haptic effects which are not clearly positioned on the *Adaptability* scale. They also suggest that *Context Adaptability* is the most important ergonomic property of the haptic effects, which is in agreement with the expert reasoning.

Nevertheless, the global behavior of the fuzzy model on the analyzed set of haptic effects is considered by the expert to be congruent with his own ergonomic vision on vibrotactile perception. Moreover, the model performance indicators are considered relevant, as for most of the effects, the system predictions match the subjective evaluations of the expert, within a reasonable interval.

5. Conclusion

In the present paper a fuzzy expert model of haptic perception for automobile touch-screen displays was proposed. The model presents an ergonomic vision on vibrotactile perception, and decomposes the notion of "haptic comfort" onto a series of sensory properties, which are specific to the automotive industry, e.g. *Adaptability*, *Neatness*, and *Sensation of Displacement*.

A set of 48 haptic effects, generated on a state-of-the-art experimental device, were evaluated by an expert in automotive ergonomics and interior controls. These evaluations fully characterize the ergonomic features of the haptic effects, as well as their induced comfort degree.

Based on the above evaluations and using an interpretable linguistic rule-base, a fuzzy symbolic model was defined. The model achieves a global error rate of 14.6%, and manages to correctly predict the comfort degree for 89.6% of the haptic effects studied, within a predefined precision threshold. Therefore, the model was found to be in agreement with the expert's ergonomic knowledge on the matter, and it could be used for more complex haptic effects, such as those associated with virtual knobs or sliders.

An interesting perspective would be to test the proposed model for touch-screen aeronautical instrument panels, given the similarities they bear with automobile tactile interfaces. In this regard, the evaluations of an expert in aeronautical cockpit design, member of the MISAC consortium, could be used to validate or adjust the proposed model.

Acknowledgment

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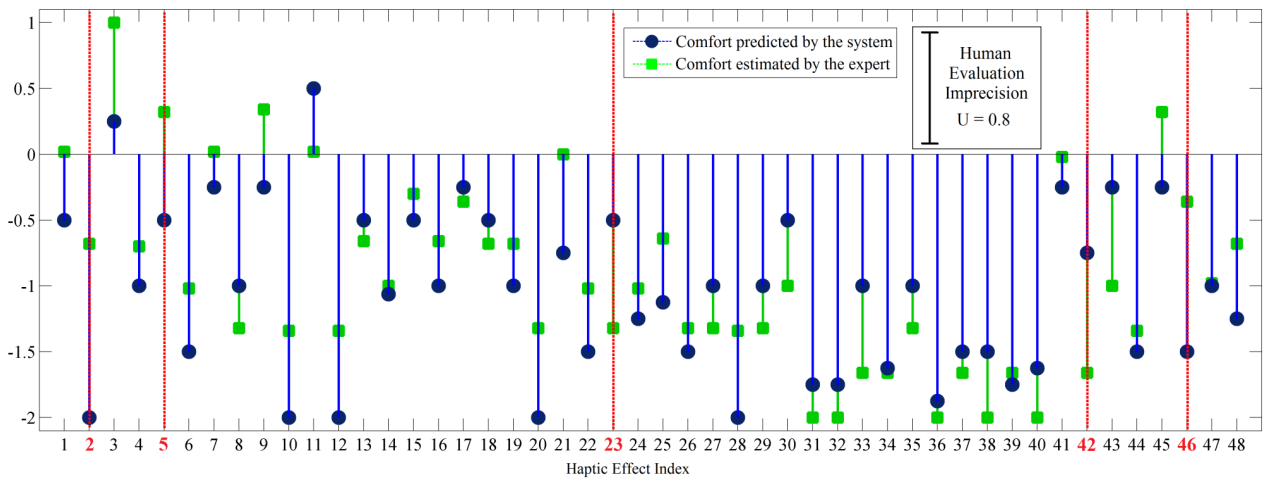

Figure 3: Comparison between the predicted and actual comfort degrees for the set of 48 haptic effects. In the above figure, the abscissa holds the indexes of the different haptic effects (in no particular order), while the ordinate axis represent the numerical scale of attribute *comfort*.

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