A Holistic Comfort Model for Virtual Cabin Designs

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Abstract Holistic comfort models are becoming increasingly important for the design and virtual evaluation of advanced automotive cabin and occupant experiences. Whereas for manual driving the main driver tasks have been relatively fixed, with the advent of automated driving the possible occupant activities dramatically increase which should influence the experience of comfort. The question is how trade-offs between comfort, efficiency, and costs can be balanced to create optimal cabin designs: How much do entertaining or time-saving activities like watching movies or reading reports influence the overall experience of comfort? Compared to this, how important is physiological comfort toward the overall experience of comfort? Such questions are investigated in the European research project DOMUS that is addressing the challenge of increasing the range of electric vehicles by 25% in different ambient conditions while maintaining or improving the experience of comfort of driver and passengers.

As part of this project we are postulating a holistic comfort model that is based on existing comfort models and extend them to include the experience of satisfaction as a main second factor beside physiological comfort. We then report the results of the first study to investigate the connection between the vehicle occupants' activities and their experiences of acoustic comfort.

Participants performed a motoric tracking task at three levels of difficulty while hearing the sound recordings of either one of two electric vehicles. The results indicate that at increased activity levels participants also reported greater acoustic discomfort for bother types of vehicle sounds. The results are consistent with the postulated holistic comfort model and we discuss the implications and planned next steps to test and expand the model.

Keywords: Holistic comfort model, auditory comfort, mobile tracking task, virtual development, automotive comfort.

1 Introduction

Increasing virtualization of vehicle design and development pushes design and development processes from physical prototypes to digital environments. Physical prototypes are expensive and take a long time to build whereas novel markets require faster and more flexible design processes. Especially the prospect of automated driving functionality opens a new chapter of designing vehicles that go even further beyond mere physiological comfort considerations. In such vehicles, there exist considerably more trade-offs between design variations to achieve an acceptable balance of passenger experience, functionality, technical efficiency, feasibility, appearance, and costs. These trade-offs can be addressed using virtual design processes to quickly evaluate the large number of permutations of possible designs. However, such processes require appropriate digital models of human behavior and perception. While this push for virtualization can be observed in automotive developments they are also applicable to other domains where environments are being designed for humans such as in aviation, building, and city architecture. Therefore, models of human comfort are now being adopted for virtual developments. Specifically, single-dimensional comfort such as seating, acoustic, or thermal environments are starting to be combined into multi-dimensional, holistic human comfort experience models.

The connection between comfort and vehicle cabin designs is being investigated in the European Horizon 2020 DOMUS project (https://www.domus-project.eu/) that investigates cabin design interventions to increase the range of electric vehicles while at the same time support acceptable human comfort. In this project, different design strategies are virtually evaluated for their potential to increase driving range while at the same time achieving acceptable comfort experiences. Comfort and efficiency thereby represent competing objectives that need to be investigated at the same time to identify acceptable trade-offs. This requires the use of holistic comfort models.

In this paper we propose a model of holistic comfort that is based on existing multi-dimensional comfort models and adapt it for the purpose of automotive cabin designs. We then report a first experimental study to investigate the impact of workload on acoustic comfort. We discuss the findings in the light of the holistic comfort models and propose a concrete additional study to confirm and expand the model further.

1.1 Toward Holistic Comfort Models

Comfort expectations for automotive vehicle cabins go beyond mere physiological comfort as indicated by the inclusion of many non-driving related features such as entertainment and information systems and aesthetic styling characteristics. Especially as driving gets automated these trends are expected to accelerate as vehicles become increasingly places to work, communicate, and relax. Even in today's modern vehicles, designers speak about empathetic assistants1 who sense human emotions and appropriately adjust to provide optimal occupant experiences. This leads toward a wider understanding of comfort that goes beyond physiological comfort: sitting in a comfortable chair at perfect room temperature for extended time may not result in the experience of overall comfort if the experiencers activities are not taken into account. Therefore, it seems that in order to understand the comfort experiences of modern drivers and passengers comfort models would need to incorporate the human experience to a greater extent. Whereas physiological comfort is mainly influenced by the interaction of the body with the environment, a positive experience of holistic comfort, we think, needs to take into account the experience of satisfaction in the vehicle environment. Human satisfaction experiences have been investigated in many areas, but especially in product design (e.g. [1], [2]) and work places where factors of satisfaction include autonomy, control, tasks and task identification (e.g. [3]).

According to the comfort theories of [4] comfort is influenced by the interaction between the human, the activity, the product, and the environment which results in body sensations that are modified by comfort expectations, resulting in feelings of comfort, discomfort, or no feelings.

[5] expanded this model toward mattress comfort and measured the impact of expectation on comfort judgements. We are expanding this model further by including psychological moderator processes for two different types of comfort aspects: physiological comfort perception and the experience of satisfaction, see Figure 1. Each of the main components is briefly discussed next.

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[1] https://readwrite.com/2018/01/18/empathic-ai-next-generation-vehicles-will-understand-emotions/

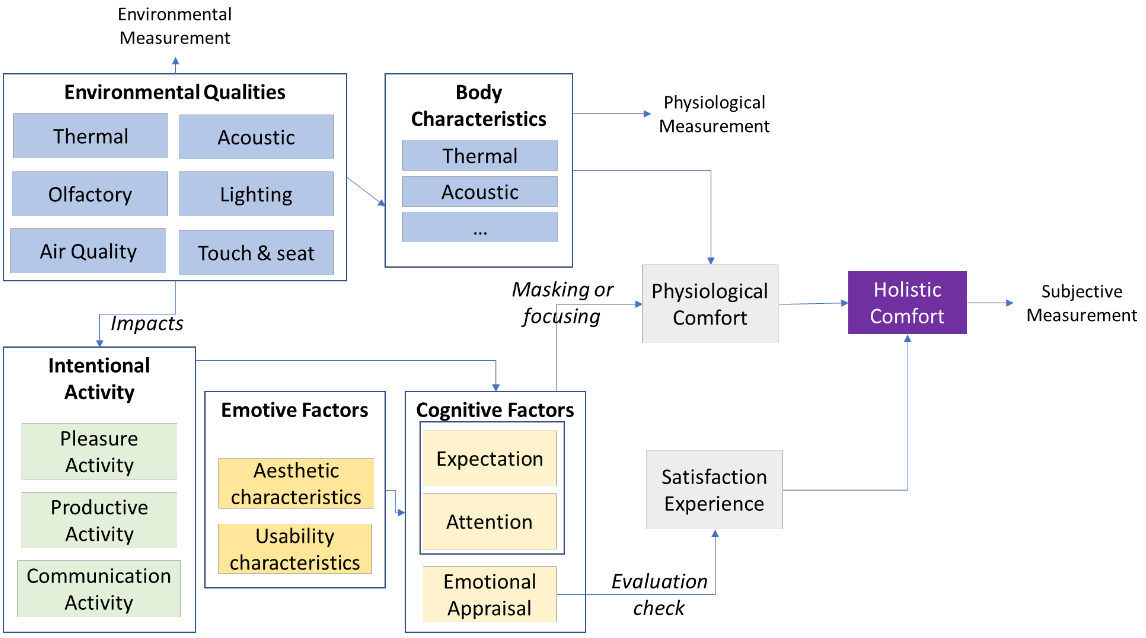

Fig. 1. Holistic Comfort Model

Environmental qualities describe the aspects of the environment with which the human body interacts as basis of a physiological comfort assessment. In the Vink-Hallbeck model [4] these qualities are ordered around person, product characteristics, and usage/task as well as the working environment, but in the end what is sensed by the human body are thermal, acoustic, olfactory, lighting, haptic and seating, and air-quality characteristics.

The specific body characteristics interact with the environmental characteristics so that physiological sensations are formed as indicated in Vink-Hallbeck's model [4]. Clothing for example influences thermal sensations and the shape of the body impacts the seating comfort experience. Both, body characteristics as well as the interaction between environmental qualities and body characteristics can be measured using physiological measurements.

The experience of physiological comfort is moderated by cognitive factors effectively masking or emphasizing the physiological perceptions. This moderation effect of cognitive processes on perception is for example in the focus of the investigation of chronic pain [6]. Also, [7] investigated the comfort of passengers while sitting for a prolonged period of time (e.g. in-flight entertainment) and environmental conditions have been shown to impact passenger comfort. This may be explainable by the fact that attentional resources are pulled from the physiological experience toward other areas or activities which may allow to endure comfort over prolonged amounts of time. Comfort expectations may further attenuate the physiological comfort thresholds: people report experiencing the comfort of a mattress to be higher when it is introduced as a high-quality product versus a low-quality product [5].

Intentional activities represent the activities that the vehicle occupant is engaged in and form the basis for the cognitive appraisal processes of satisfaction or dissatisfaction. Aspects of satisfaction in the work context are listed for example by [3] and include autonomy (see e.g. [8]), level of control, skill variety, task significance, and identity as well as feedback. User satisfaction models have been postulated in the design community (e.g. [2] and [1]). Altogether, these factors are different from physiological factors requiring an emotional appraisal process rather than for physiological comfort. Whereas the perception and evaluation of physiological comfort is based on expectations and the availability of attention to filter, suppress, or emphasize the physiological perceptions, emotional appraisal processes should be involved in the decision concerning the experience of satisfaction or dissatisfaction (see e.g. [9]). The activity itself becomes part of the comfort experience. The environment may more or less support the conduct of these activities. Furthermore, emotive product characteristics such as aesthetic and usability may further strengthen the experience of satisfaction.

1.2 Research Questions

The proposed holistic comfort model has several predictions that can be empirically investigated. The first prediction is that cognitive factors influence the perception of physiological comfort. Specifically, if the physiological characteristics of a given environment do not support the performance of an intended task, the physiological comfort should be perceived to be lower. We investigated this by changing the difficulty of a motor task that requires eye-hand coordination and measured the impact on acoustic discomfort. The motor task however did not require cognitive auditory processing. Performing the task at a higher difficulty level should lead to lower acoustic comfort in the presence of a constant noise that is loud enough (see e.g. [10] for a widened interpretation of the Yerkes-Dodson law). Therefore, we expect that the higher the noise level the higher the perceived discomfort.

In the following, we report a first pilot study that we conducted to investigate this prediction of our model. While the study was originally intended to test the study materials and general feasibility of this concept, we found the results to be significant, both statistically and theoretically. Therefore, we present these results next.

2 Method

The pilot study investigated the influence of three levels of workload on the participants' perception of acoustic discomfort. Eleven participants, 8 of them male and 3 female participated, their mean age was 38 years. After participants completed a sociodemographic questionnaire they indicated their individual noise sensitivity on a noise sensitivity questionnaire [11]. The scale contains 21 items to assess noise sensitivity on a 6-point scale. The items asked the participants to indicate their attitudes toward noise and their emotional reactions to a variety of environmental sounds encountered in everyday life. Then participants were asked to perform a motoric task at either one of three difficulty levels while hearing either one of two electric vehicle sounds through a headset, see following subsections. The participants completed altogether 6 trials (three motoric task difficulties x 2 sounds in a complete within-subject design). The order of the trials was randomized to account for order effects. After each trial, participants indicated their experienced workload using the NASA TLX [12]. Participants were also asked to indicate their acoustic discomfort (annoyance or "Störung" in german) using the Magnitude Estimation Technique (MET, [13], [14]). After the 6 trials, participants rated the sounds using 23 descriptors that were derived from literature, see [15], see Table 1, on a 9-item scale.

Table 1. Adjectives for Psycho-acoustic Evaluation

Loud	Strong	Sharp	Rough
Discrete	Beautiful	Muted	Attractive
Crackling	Comfortable	Whistling	Relaxed
Special	Faultless	Clear	Frightening
Harsh	Sturdy	Stable	Shaking
Monotonous	Growling	Rushing	

2.1 Sounds

To assess the impact of sound quality, the sounds of two different electric vehicles were recorded. The sounds for vehicle A were recorded in a Tesla Model S whereas vehicle B sounds were recorded in a Citroen C-Zero, see Figure 2. Throughout the experiment, participants were not informed about the source of the vehicle sounds. Recordings were made using a bi-aural microphone positioned at ear-height of the passenger seat using an artificial head. During the recording the vehicles were driven at a constant 100km/h. The measured sound pressure levels were 64 dBA for vehicle A and 70 dBA for the vehicle B. These levels were reproduced during the experiment where participants listened to the sounds on a Sennheiser HD25-1 headset.

Fig. 2. Electric Vehicles A and B for which sounds were recorded

2.2 Tasks

The workload inducing task was a critical tracking task [16] as implemented by the mobile tracking task application [17]. Participants were asked to keep a circle in the cross-haired center of a handheld tablet that moved as the tablet was tilted, see. Figure 3. The parameter settings were set as indicated in at x, y, and z, resulting in increasing difficulty in keeping the circle in the center.

Table 2. Used MTT Parameter Settings

Parameter	*Easy*	*Medium*	*Difficult*
Sensitivity	5	20	30
Instability	0	15	25

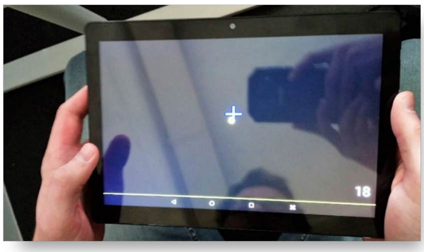

Fig. 3. Mobile Tracking Task

3 Results

As expected, did the participants self-reported workload levels differ between the three task difficulty levels, see Table 3. The ratings were averaged across NASA TLX scales (scale 5, effort, was reverse coded) and transformed onto a scale from 0 to 10, 10 indicating maximal subjective workload. The task difficulty effect was statistically highly significant as indicated by a repeated measures ANOVA (F df=2,20 = 24.98, $p < 0.001$ after Greenhouse-Geisser (GG) adjustment due to slight violation of the sphericity assumption). These results serve as confirmation that our experimental tasks indeed led to differences in perceived workload.

Table 3. Mean subjective workload ratings (NASA TLX) per condition

Measure	*Easy*	*Medium*	*Difficult*
Mean	3.49	4.35	4.56
Std	0.61	0.74	0.50

Participants indicated their perceived acoustic discomfort by the drawn length of a line as well as by stating a number. These two types of measurements were, as expected, highly correlated with each other (r(90) =

0.95, $p < 0.001$) so after standardizing and normalizing them, the two types of measurements were averaged and used as an overall indicator for perceived acoustic discomfort. A repeated measures ANOVA with the two within-factors vehicle type and workload level revealed two significant main effects of vehicle type (Fdf=2,20 = 17.93, $p < 0.01$) and workload level (Fdf=2,20 = 5.5, $p < 0.05$) after GG adjustment as indicated above. The interaction between the two factors was not statistically significant. The sounds of vehicle A were found to be less uncomfortable than the sounds of vehicle B. As result, perceived acoustic discomfort was different between the two vehicle sounds and also differed dependent on workload levels: in the higher workload conditions, acoustic discomfort was also perceived to be greater for both vehicle sounds, see Table 4 and Figure 4. We had hypothesized that the interaction of the two factors would also be significant such that the increase in discomfort should be steeper with the less comfortable noise type. However, this could not be confirmed.

Table 4. Mean Acoustic Discomfort MET ratings (Standard deviations in parentheses)

Measure	*Easy*	*Medium*	*Difficult*
Workload	3.49 (0.61)	4.35 (0.74)	4.56 (0.5)
Discomfort (Tesla)	0.16 (0.21)	0.32 (0.23)	0.45 (0.39)
Discomfort (Citroen)	0.47 (0.35)	0.71 (0.25)	0.77 (0.23)

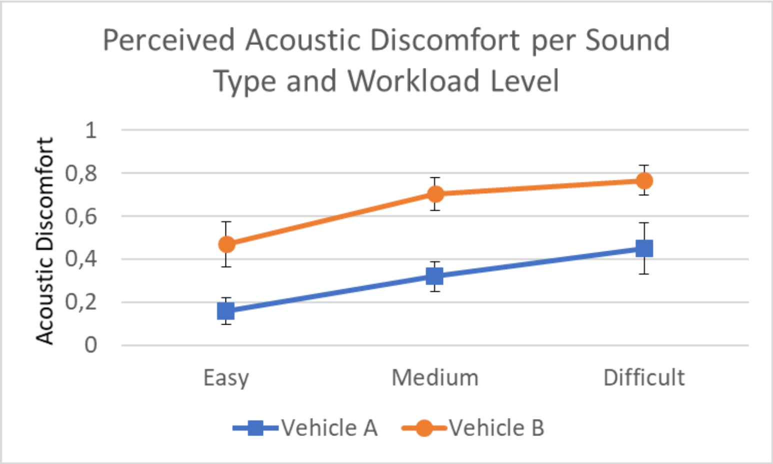

Fig. 4. Mean and standard errors of acoustic discomfort measurements

Participants found that the sounds differed on some of the 23 acoustic aspects on which they had assessed the sounds. Statistically significant using a t-test were found for the following characteristics: Sound B was found to be louder, stronger, sharper, and rougher than sound A. Sound A instead was found to be more discrete, more beautiful, and more muted. These ratings confirmed that the participants were actually able to perceive differences in the sound qualities.

4 Discussion and Conclusions

In this paper we presented a holistic comfort model and reported the results of a first pilot study to evaluate connections between experienced workload and acoustic discomfort. It was found that acoustic discomfort was influenced not only by the sound quality but also by the experienced workload level. Acoustic discomfort was found to be greater at higher workload levels for both types of sound. We had hypothesized this in the model as the physiological environment interacts with the tasks that need to be performed. While this is consistent with the presented holistic comfort model, we also had expected an interaction between sound type and workload level such that the less comfortable sound would cause an even steeper increase in discomfort than the more comfortable sound. This was not found to be the case.

The current study only investigated the link between experienced workload and acoustic discomfort, but not holistic comfort for which we need a more immersive environment. Therefore, in our next study we ask participants to drive a vehicle in a driving simulator and give them different tasks while exposing them to a more realistic acoustic environment compared to the one assessed in this study. We expect that the different task types will trigger different impact on the holistic and acoustic comfort perceptions and therefore allow to differentiate between the explanations given in this study. We will soon report the results of this study.

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