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Abstract

In this paper, a literature study is presented on the types of objective measures that can contribute to the prediction of (dis)comfort, the feasibility of measuring those factors, and the potential of building a model based on them. Results indicate that in addition to subjective measurements, objective measures might help us to understand the process towards comfort or discomfort better, and some of them might be used as predictors in modelling comfort/discomfort.

Keywords

Comfort, discomfort, measure

Introduction

Improving comfort and reducing discomfort are the wishes of designer of a product, service or environment. While the product/service/environment itself cannot be comfortable, the user speaks during and after the use of it (Mansfield et al. 2020). Such comfort experience can be summarized as “a pleasant state or relaxed feeling of a human being in reaction to its environment” and the discomfort experience is “an unpleasant state of the human body in reaction to its physical environment” (Vink and Hallbeck 2012). In comparison with comfort, the feeling of discomfort is more associated to the physical interactions between the user and the product/environment.

In the measurement of the levels of (dis)comfort of a user, subjective measures are still the “golden” standard. Researchers developed many useful questionnaires for evaluating the levels of (dis)comfort in different design phases for different applications (Anjani et al. 2021). However, the process of using subjective measures is often time consuming and the results are prone to inter- and intra-observer variabilities (Ramkumar et al. 2017), and sometimes it is even difficult for the users to complete a comfort questionnaire while using a product. Besides, though it is possible to study (dis)comfort in the use of products/services based on the outcomes of questionnaires, it might be a challenge to detect them in real-time, and apply possible interventions if needed. In addition, in explaining the questionnaire outcomes, measurements of a certain physical phenomenon might be helpful. For this, objective measures of (dis)comfort are useful additions.

While the word (dis)comfort offers a nice cosmetic coating of the phenomenon, it has a lot constructs (Mansfield et al. 2020). Those constructs are associated with the users’ backgrounds, the expectation(s), the (social) environment(s), the product(s) he/she is using, the interactions between the user and the product/environment, and the duration of the use (Naddeo 2017). All of these form a multi-factorial model (Mansfield et al. 2020). Though complicated, factors that can be objectively measured, or inferred from other related measurable parameters, might be useful in quantifying (part of) this phenomenon in a specific context.

In the European project COMFDEMO, researchers are working on modelling the (dis)comfort experience of passengers sitting in the aircraft cabin. The purpose of this paper is to make an investigation of the types of objective measures that can contribute to the prediction of (dis)comfort, the feasibility of measuring those factors, and the potential of building a model based on them.

Materials & Methods

We searched in the databases Web of Science, Scopus and PubMed with the search term "Comfort AND Discomfort AND Measurement". The numbers of found records were 589, 869 and 1089, respectively. After removing duplications, 1767 records were identified. By screening all abstracts with the criterion of "using objective measures to evaluate (dis)comfort", we identified 284 relevant papers. This number was further refined to 190 after reading the full papers. These studies can be categorized according to different criteria: the product/ environment to be evaluated, the types of user activities, the measures, etc. Characteristics of these studies will be described in the results.

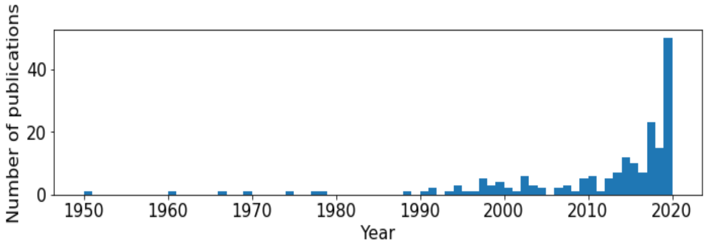

Figure 1: The number of comfort studies using objective measures

Results & Discussions

The selected 190 studies indicated that from 1950s, researcher started to pay attention to the objective measures of the perceived (dis)comfort of users in the use of different products/services/ environments. Recently, this research topic attracted more attention as Fig.1.

Product (environment) being investigated

(Dis)Comfort is evaluated in different environments with different populations. While the building environment (33 of 190) and seats in transportation (67 of 190) were the focus of researchers, clinical environment also attracted much attention. Besides, screens (incl. Head Mount Display), hand tools (incl. handles, glove, smart phone), respirator facepieces (incl. masks), shoes (incl. insole), protective clothes were also investigated. An important finding is that recently, researchers also paid much attention on the perceived comfort in using personalized products, especially personalized medical products (Jeong-Hoon Yang, Shinsuke Kato, and Ho-Tae Seok 2009)(Paternò et al. 2020), due to its uniqueness nature.

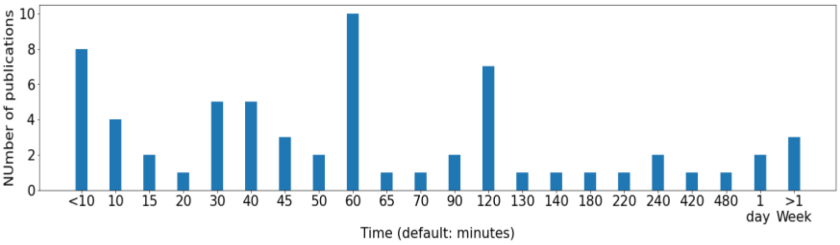

Figure 2: Time duration of the measurement

Time durations of the studies

The feeling of (dis)comfort can be influenced by time where the level of discomfort often increases over time in the use of the product (Sammonds, Fray, and Mansfield 2017). Figure 6 lists the numbers of studies versus the time duration of these studies. It shows that less than 10 minutes, 30~40 minutes, 60 minutes and 120 minutes are often selected by researchers, mainly due to that: 1) studies suggested that the effect of (dis)comfort regarding the use of product/ environment is significant after 40 minutes exposure (Mansfield, Sammonds, and Nguyen 2015); 2) the time duration in the usage scenario, e.g. in the use of a bike (Gomes and Savionek 2014), a trip is often within 120 minutes and in the study of comfort of standing on a floor (Zander, King, and Ezenwa 2004), researchers set the exposure time same as the length of a working day (8h); 3) practical constrains in the study, e.g. in the evaluation of keyboards, one study set the duration as 5 -10 minutes (Smutz, Serina, and Rempel 1994) and another set the duration as 120 minutes (Liao and Drury 2000).

Measures

In Figure 3, we list the objective measures that are used in the selected studies regarding different applications. In the following, we summarize the findings according to temperature & air quality, vibroacoustic environment, physiological and physical measures of the subject.

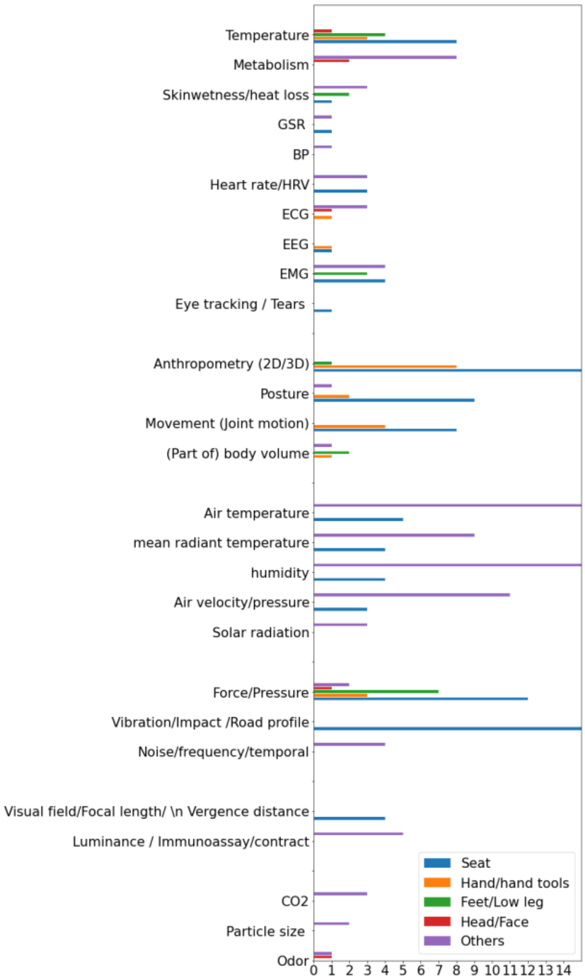

Figure 3: Measures used in the selected studies

Temperature & Air quality

In the study of thermal environment, four physical variables, the air temperature, the mean radiant temperature, the air velocity and the relative humidity, are often mentioned according to the ISO7726 (Gameiro da Silva 2002). For the air temperature, females became aware of thermal discomfort before males under low air temperature conditions (Hashiguchi, Feng, and Tochihara 2010). Regarding the humidity, it was indicated that the most comfort relative humidity range is 30%-50%. However, in the use of products and in some environments, the levels of humidity may differ around human bodies. For instance, Dell and Romitelli (Della and Romitelli 1993) found that the feeling of humid warmth in the body area in contact with seat becomes the most important. Air velocity may influence the perceived comfort, especially regarding the thermal comfort experience by influencing the convective heat transfer coefficients. Sakoi (Sakoi et al. 2007) indicated that the peak of the overall comfort sensation appeared around a mean sensible heat loss of 40 W/m^2. However, even if the mean skin temperature and the mean sensible heat loss were kept constant at 34 °C and 40 W/m^2, respectively, the overall comfort sensation tended to decrease with an increase in the magnitude of environmental thermal non-uniformity.

Besides these four major factors, the concentration of CO_2 and the odour might also influence the feeling of comfort. The range of CO_2 concentration may differ from 577 to 1787 ppm in a classroom, and high concentrations of CO_2 (e.g. due to poor air ventilation) may lead to significant difference between the performance of students (Vilcekova et al. 2017). The odour might also influence the perceived (dis)comfort of users over time, however, the scent preferences differ a lot among a population (Yao, Song, and Vink 2021).

Black-globe thermometers were often used in the measurement of mean radiant temperature. The air temperature, the humidity, the CO_2 concentration, the air speed of the environment are often measured by air quality monitoring systems (Huang and Kang 2020). (Zhang and Srinivasan 2020) gave an overview of these devices regarding the ability, the accuracy and the cost. In measuring the humidity around human body, smaller humidity sensors were selected by researchers (Paternò et al. 2020). Earlier works of using odour sensors to evaluate comfort was reported by (Hamanaka et al. 1997). Recently, different types of odour sensors, e.g. e-nose, are developed as summarized by (Hu et al. 2019)

Vibroacoustic

Vibration: Vehicle occupants can feel a wide range of frequencies, from less than 1 Hz to more than 300 Hz (Griffin 2007). For the whole-body vibration, a seat (and the backrest) usually attenuate high frequencies, and a bandwidth from 0.5 to 80 Hz is considered sufficient in ergonomics evaluation (ISO 2018). Although the seated human is especially sensitive to vertical vibration in the 4.5-5.5 Hz range, vibration and shock should be attenuated as much as possible, as in practice the lower and higher frequencies might influence the feeling of comfort as well (Wilder et al. 1994). The judgments of discomfort caused by stimuli having a common waveform were significantly increased by an increase of 6-12% in the magnitudes of the stimuli (Matsumoto and Griffin 2002). For hands and feet, there may be a direct contact with the product without attenuation by compliant materials. The frequency of hand-transmitted vibration can be up to 1000 Hz, although experimental data are difficult to acquire at such high frequencies (Griffin 2007).

To measure the vibration up to 80 Hz, according to the Nyquist law, the sampling frequency should be at least 160 Hz, preferably even higher for preserving more information in the original signal. Piezoelectric accelerometers are the most popular choice in industrial applications (Wijaya, Jönsson, and Johansson 2003). However, the sizes of these types of sensors are large and the cost is often high. In the past decade, capacitive MEMS accelerometers are widely used in measuring vibrations due to its small size, efficient power usage and low cost. However, the quality of acquired data is also low compared to data acquired from piezoelectric sensors, especially regarding high frequency and amplitude. More efforts are often needed in the post-processing (Han et al. 2020).

Noise: Occupational Safety and Health Administration (OSHA) requires employers to implement a hearing conservation program when noise exposure is at or above 85dB averaged over 8 working hours, or an 8-hour time-weighted average (Occupational Safety and Health 2021). However, it does not mean that the experienced noise lower than 85dB is comfortable. Different groups of people may have significantly different opinions on the acoustic comfort regarding the same noise (Al-Arja 2020), due to different intentions and exposure durations. Noise and vibration often occur simultaneously and the ‘masking effect’ regarding comfort is inevitable (Huang and Griffin 2012), i.e. high amplitude of vibrations may “cover” the changes of lower noise levels and vice versa. In the context of the airplane, noise at 70–88 dBA level cannot be “covered” by the vibration (Huang and Griffin 2014). For the noise at the same loudness, the subjective feeling might differ according to its spectra in the frequency domain as well (Vernet and Vallet 1977). For instance, (Li and Huang 2018) built a series of models regarding acoustic comfort of passengers on different road based on the loudness, the sharpness, the roughness, and the articulation of the sound.

The loudness of sound (in db/dBA) can be measured by decibel meters where a free-field microphone is often equipped. Considering the wide range of the loudness of noise levels in the daily life (e.g. 50 dbA/office, 75 dbA/outside), a class II device with ±2db accuracy might be enough in the study of acoustic comfort. The characteristic of sound can be acquired by analysing the sound records using software tools, e.g. by ArtemiS SUITE (Li and Huang 2018). However, ethical issues should be addressed as the voices of subjects and researchers are often recorded as well.

Physiological Measures of the user(s)

Though the psychological feeling of (dis)comfort does not necessarily be reflected on physiological measures, there are many relationships between them. Physiological measures convey precise information about an individual’s bodily functions, and many of them, e.g. EEG, ECG (incl. HRV), EMG, were found to be related to the feeling of (dis)comfort in different contexts. As the measurement device itself might influence the feeling of comfort, e.g. it is difficult for the user to neglect the feeling of the EEG cap while evaluating the level of comfort in the use of a product, in this short review, we focus on several non-intrusive physiological measures only.

Skin temperature: In the studies focusing on thermal comfort, the skin temperature at different locations was always recorded. In more detailed studies, researchers also measured the rectal, muscle, finger and trunk temperate. Thermometers and thermistors were often used to measure the temperature of the skin and for measuring the temperature of the skin which is exposed to air, using infrared thermometers/cameras is getting more popular due to its non-invasive nature (Cosma and Simha 2019).

HRV: Hear rate variability (HRV) is often used in studies where the emotional stimulation is relatively strong (Choi et al. 2017). As human emotion and the feeling of comfort have strong relationships (Naddeo and Cappetti 2021), HRV was used in several studies related to comfort (Liu, Lian, and Liu 2008). More than 30 HRV features can be extracted from the acquired RR intervals of the subjects, and they can be classfied to time-domain, frequency-domain and non-linear features (Shaffer and Ginsberg 2017). Among them, time domain features SDNN, pNN50, RMSSD and frequency domain features LF/HF (Lorenzino et al. 2020) were often used in comfort evaluation. HRV features can be extracted from ECG signals in a clinical setup, however, the ECG measurement itself might be intrusive for the users. Recently, many wearables, e.g. Scosche Rhythm24, were introduced and they are able to log real-time RR intervals. Such a function might facilitate researchers in different comfort studies.

Galvanic Skin Response (GSR) is an "electrodermal" signature of the sympathetic nervous innervation of the skin, and it reacts sensitively to emotional provocation, salient thoughts, and attentional demand (Nagai, Jones, and Sen 2019). Similar to the use of HRV, GSR can be used to detect the emotional aspect of comfort. GSR devices with finger electrodes are widely used. Recently, low-cost wearable GSR sensors were also introduced by researchers in the evaluation of human emotion (Kyriakou et al. 2019).

EMG: EMGs of certain muscles are correlated with the comfort feeling while seated. The slumped sitting posture is most likely associated to relaxing as it puts a minimum of stress on the back and neck muscles (Zhao and Tang 1994). Accordingly, Franz et al. developed a massage system to reduce the muscle activity in the shoulder and upper back for increasing comfort (Franz et al. 2011). On the other side, prolonged muscle activities may lead to discomfort, e.g. standing for 2h shows muscle fatigue (Hansen, Winkel, and Jørgensen 1998), which can be identified by a fall in the centre frequency (Chiu and Wang 2007). SENIAM recommends that the bandwidth of wearable sEMG (surface EMG) systems should cover a frequency range from 20 Hz to 400/500 Hz (Hermie J Hermens 1999). In the analysis of the data, the RMS of the acquired sEMG signals is one of the most reliable features in the time domain analysis. In the frequency domain, researchers often took the slope of MPF versus time as an indicator for local muscle fatigue (Balasubramanian, Jagannath, and Adalarasu 2014). For acquiring sEMG signals, as the amplitude of signals are in the range of 1 to 10 mv, the SNR of signals acquired by dry electrodes is generally lower than using wet electrodes. However, using dry electrodes is more convenient for a non-professional setup (Prakash, Sharma, and Sharma 2021).

Eye tracking: In the study of screen related activities, eye tracking is an important tool in the evaluation of visual comfort (Han et al. 2021). Eye blinks, fixations and saccades are often used in comfort studies. Besides, gaze point, the pupil size, focus point and crossed disparity are also mentioned in the evaluation of visual comfort (Abromavičius and Serackis 2018). Tobii eye trackers (Tobii 2019) might be the most popular choice for acquiring eye moments information. Recently, new development in image processing made tracking the movement of eyes via Webcams also possible (GazeRecorder 2021), which greatly increases the potential usage of eye tracking in the research on visual comfort.

Physical Measures of the user(s)

Regarding the physical aspects of the user, age, gender, anthropometric measurements (incl. 1D, 2D and 3D), posture, body/joint motion (incl. fidgeting), volume of (part of) the body and (reaction) force/pressure applied on the (part of) body are often used in comfort studies.

Anthropometry: Bouwens et al. (Bouwens et al. 2018) indicated that anthropometry is the most crucial factor influencing the perceived comfort of passengers in an aircraft seat. The selected anthropometric measures differ among studies regarding the products and environments to be evaluated. In the context of sitting comfort, age, gender, weight, BMI, hip-width, leg length and sitting height were often measured. Regarding measurement methods, besides self-reporting and 1D measures, 2D imaging and 3D scanning techniques are often used by researchers to accelerate the process and improve the accuracy, though the post-processing might be demanding regarding both time and the manpower (Tony and Alphin 2019) (Yang et al. 2021).

Posture changes/motion: In the use of different products, a user might change her/his postures not necessarily related to the use of product. In the context of sitting, (Sammonds et al. 2017) classified those movements as movements of the limbs, the torso and the whole body. They also found that the number of independent movements is correlated with the level of perceived discomfort. Many methods were used to detect movements of the body. The easiest might be conducting a blob analysis on the adjacent frames of video recordings. A more precise measurement can be achieved by coded fiducial markers (Fiorillo et al. 2019) or motion tracking system (Asundi et al. 2010). Pressure sensors/mat can also be used to detect motions of a subject (Aziz et al. 2020). Using wearable sensors are also popular choices (Han et al. 2021)(Bootsman et al. 2019). As movements of the body are often associated with motions of joints, acquiring EMG signals of relevant muscles can be used as an indirect method to detect movements of the body (Liu, Niu, and Zhou 2020).

Pressure/Force: A long-time exposure to large forces/pressures often results in discomfort. Researchers measured the force/pressure in comfort studies regarding the spinal load (De Looze, Kuijt-Evers, and Van Dieën 2003), the (lower) leg (Zander et al. 2004)(Sessoms et al. 2020), the hand (Kamel, Hakeem, and Tantawy 2020), etc. Forces on different parts of the body can be measured by different devices, e.g. force on the hand can be measured by a dynamometer (Kamel et al. 2020). In most cases, pressure in comfort studies was measured by sensors such as the force sensitive resistor (Ma et al. 2017). For a relatively large area, pressure mats in different forms (e.g. (XSensor 2021), (Tekscan 2020)) were often used.

Implication

Ergonomics evolves with evolvement of the digital era. In the 2020 hype cycle, Gartner enlisted the digital twin of the person as one of the most promising emerging technologies (Panetta 2020). In 2021, they further strengthened the concept with three strategic directions: internet of behaviours, total experience strategy and privacy-enhancing computing (Panetta 2021). While these trends highlight the needs of a quantitative (dis)comfort model in different contexts as part of the digital shadow/twin of the person (He, Song, and Wang 2021), the only one who decides on comfort is the end-user. However, predictions can support the design of environments/ products/service as by measuring, we do understand the process towards comfort or discomfort much better (Anjani 2021).

This short review is more a starting point of comfort modelling rather than a conclusion. Based on this review, it seems that building a quantitative model regarding (dis)comfort might be a challenge, as the background and expectation of users differ. However, using a hybrid method which incorporates questionnaires for identifying the background and expectation of the subject(s), and a quantitative model on the change of (dis)comfort might be possible, providing more data is available and the use of advanced modelling tools. This is especially true for modelling discomfort, as it is more linked to the physical factors of the user (Vink and Hallbeck 2012).

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