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Tactile Information Coding for Touchless Interaction With Medical Devices by Means of Hand Gestures in the Air

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ABSTRACT

Non-contact control of medical devices in the operating room offers essential advantages. However, touchless forms of interaction such as gaze, hand and voice gesture control are poorly accepted in practical use in medicine due to insufficient feedback. Current gesture control systems usually output audiovisual feedback about a performed selection of a function. Consequently, audiovisual feedback does not relieve the already heavily loaded audiovisual perception channel of the surgeon. Therefore, the frequent request of surgeons results in a haptic feedback similar to the manipulation via a physical control element, where a direct feedback about the selection of a function is given. In this research project, the advantage of contamination-free manipulation of hand gesture control is combined with tactile feedback based on ultrasonic waves to transfer information by the tactile perception channel. The focus of the investigation is the subject's recognition of the information contents "increase", "decrease" and the marking of a "middle" or a "preferred scale value". Therefore, a virtual slider with a tactile feedback based on ultrasound waves is implemented. This slider is provided with a discrete tactile feedback in the form of a 10-point tactile scale, which can be perceived by the hand during a sliding movement. A total of 16 different coding features are tested. 4 coding features for coding an "increase", 4 coding features for coding a "decrease" and 8 coding features for coding a "middle" or "preferred value". The tactile feedback is tested on 30 subjects. The experiment consists of a main and a secondary task. The main task is to perform a precision task on a medical phantom. As a secondary task, the subjects have to perceive the change in the scale and adjust the scale position directly afterwards. The secondary task is performed blindly, without visual or acoustic feedback. The evaluation of the objective data such as task completion or operating time as well as the subjective data such as recognition of the tactile coding feature or mental load show differences between the characteristics of the coding features. With an inference statistical analysis of the results, significant differences between the different characteristics of the coding features concerning the effectiveness, efficiency and user satisfaction are identified. It's also shown that the most appropriate coding features for marking an "increase", a "decrease" and a "middle" or a "preferred scale value" need to be investigated in more detail in further studies. A particular focus of further investigations will be on the difference threshold with respect to feedback intensity and scale spacing of tactile feedback.

Keywords: Human-machine interaction, Tactile information coding, Haptics, Gesture control

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INTRODUCTION

Interaction with medical equipment during a medical procedure in the operating room poses great challenges for the surgeon. During a medical procedure, the interaction and control of medical equipment are carried out under constant compliance with strict hygiene regulations. Therefore, non-contact control of medical devices in the operating room offers essential advantages (Hurstel & Bechmann, 2019). However, touchless forms of interaction such as gaze, hand, and voice gesture control are poorly accepted for practical use in medicine due to insufficient feedback. Current gesture control systems usually only output audiovisual feedback about a function's selection. The permanent audiovisual media presence leads to an overload of human perception and information processing capability. Figure 1 gives an overview of the current heavy load on the audiovisual perception channel of surgeons. Studies by Stevenson et al. (2013) verify a very high permanent noise level in current operating rooms, which makes concentrated work very difficult. Audiovisual feedback, as provided by current gesture control systems, consequently contributes to an increase in noise levels and does not relieve the surgeon's already heavily loaded audiovisual perception channel (see Figure 1). Therefore, the frequent request of surgeons results in haptic feedback similar to the interaction via a physical control element, where direct feedback about the selection of a function is given. The aim of this work is to develop a human-machine interface that ensures safe, intuitive, and efficient interaction without interfering with the surgeon's work. For this purpose, the advantage of contamination-free interaction of gesture control is combined with tactile feedback based on ultrasonic waves (see Figure 1). Furthermore, another advantage of tactile information transfer is that this perception channel is often underutilised.

The recognition of simple information content such as an "increase" or "decrease" or an indication of a "middle" or a "preferred scale position" is the subject of this study. According to the study of Winterholler (2019), Schmid et al. (2020) or Schmid and Maier (2021), this series of experiments investigate whether information is recognized by subjects while performing an adjustment task with tactile feedback in the air.

METHOD

In the following chapter, various tactile scales are generated, which are examined concerning their suitability for the transmission of information. Information is transmitted via the tactile perception channel based on differences in the tactile scale of the ultrasound-based feedback. The focus of the investigation is the recognition of the information contents "increase", "decrease" and the indication of the "middle of a scale" or a "preferred scale value". For the characterization of an "increase" and a "decrease", four scale characteristics each are available (cf. Table 1). With regard to the tactile coding of an "increase", three further start intensities (60%, 77%, and 96%) are selected based on a feedback intensity of 48% according to the R10 series of standards (DIN 323-1, 1974). The feedback characteristic of an "increase" starts at one of these start intensities and ends at a feedback intensity

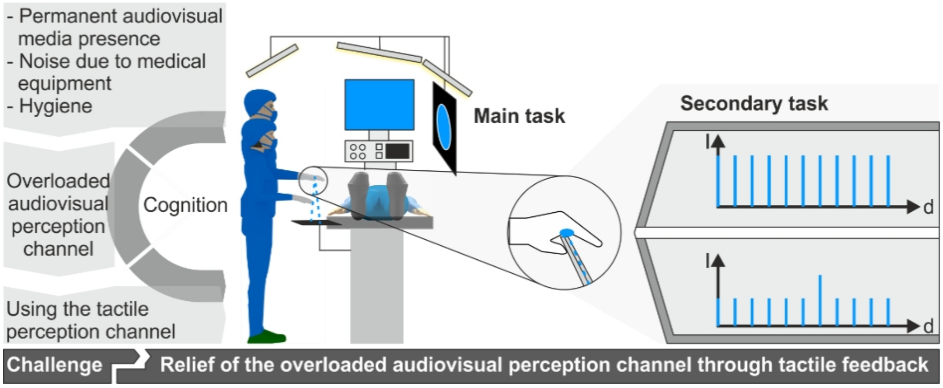
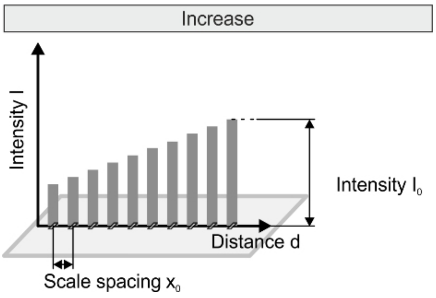
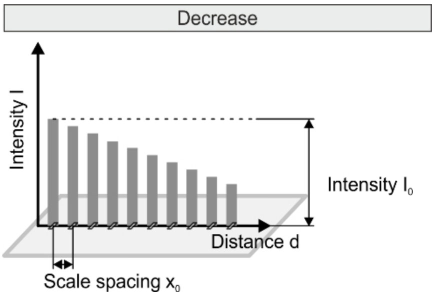


Figure 1: Visualization of the investigation target for the use of tactile feedback in the operating room.

Table 1. Scale characteristics for coding an "increase" or "decrease".

<table>
<tr><th colspan="2">Scale characteristic</th><th>Start Intensity I_0</th><th>Final Intensity I_0</th><th>Scale Spacing x_0</th></tr>
<tr><td rowspan="4">
</td><td>V1.1</td><td>48 %</td><td>100 %</td><td>30 mm</td></tr>
<tr><td>V1.2</td><td>60 %</td><td>100 %</td><td>30 mm</td></tr>
<tr><td>V1.3</td><td>77 %</td><td>100 %</td><td>30 mm</td></tr>
<tr><td>V1.4</td><td>96 %</td><td>100 %</td><td>30 mm</td></tr>
<tr><td rowspan="4">
</td><td>V1.5</td><td>100 %</td><td>48 %</td><td>30 mm</td></tr>
<tr><td>V1.6</td><td>100 %</td><td>60 %</td><td>30 mm</td></tr>
<tr><td>V1.7</td><td>100 %</td><td>77 %</td><td>30 mm</td></tr>
<tr><td>V1.8</td><td>100 %</td><td>96 %</td><td>30 mm</td></tr>
</table>

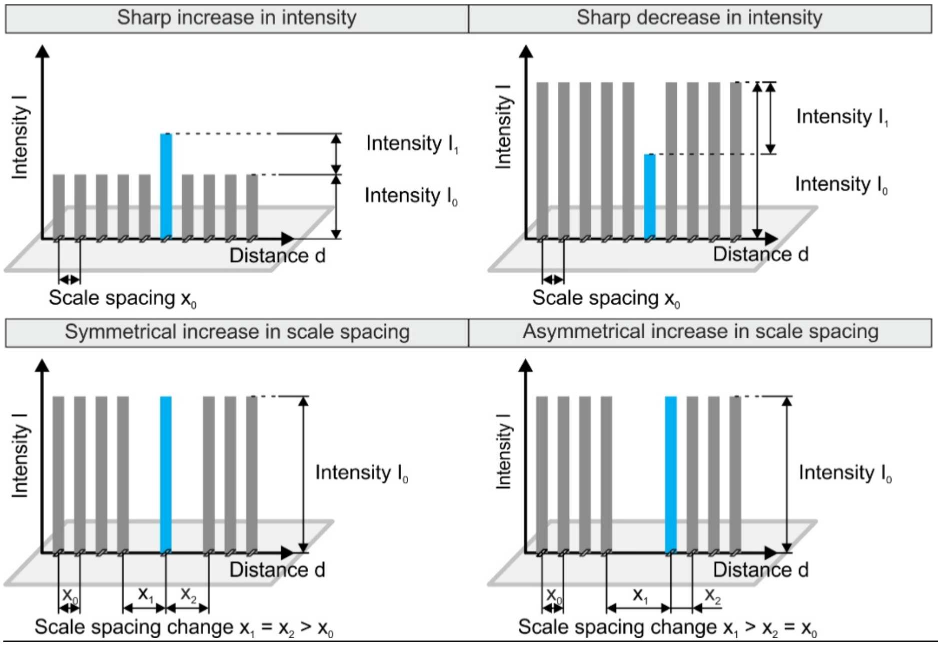
of 100%. The test subject feels a linear increase in feedback intensity when moving the hand from left to right. The gradient of the increase scale differs. A "decrease" is built up inversely. When moving the hand from left to right, the intensity decreases linearly from 100% to 48%, 60%, 77%, or 96% at the final position. Thus, four further scale characteristics are available for the feedback course of a "decrease". The "increase" as well as the "decrease" run linearly, distributed over 10 scale points.

The indication of a "middle" or a "preferred value" is done by the recognition of a difference in the scale characteristic. For this purpose, eight different feedback characteristics are implemented (cf. Table 2). The first four tactile features (V2.1 – V2.4) are composed of a sharp increase in intensity, a sharp decrease in intensity, as well as a symmetrical and asymmetrical increase in scale spacing. The second group of tactile features (V2.5 – V2.8) represents a combination of a symmetrical increase in the scale spacing with a sharp increase in intensity and a sharp decrease in intensity, as well as the combination of an asymmetrical increase in the scale spacing with a sharp increase in intensity or a sharp decrease in intensity.

Test Person

Thirty subjects participated in the study (15 males and 15 females). The average age of the subjects is 24.33 years (SD = 3.74 years, range: 19–35 years). The body height average is 174.03 cm (SD = 11.17 cm) and the corpulence average is 67.53 kg (SD = 13.48 kg). The majority of subjects have a college degree (53.30%) and are right-handed (86.70%). 56.70% do not practice a

Table 2. Tactile feature for coding a "middle" or a "preferred value".



Tactile Feature	Intensity I_0	Scale Spacing x_0	Scale Spacing x_1	Scale Spacing x_2	Intensity I_1
V2.1	60 %	30 mm	30 mm	30 mm	96 %
V2.2	100 %	30 mm	30 mm	30 mm	63 %
V2.3	100 %	30 mm	75 mm	75 mm	100 %
V2.4	100 %	30 mm	75 mm	30 mm	100 %
V2.5	60 %	30 mm	75 mm	75 mm	96 %
V2.6	100 %	30 mm	75 mm	75 mm	63 %
V2.7	100 %	30 mm	75 mm	30 mm	96 %
V2.8	100 %	30 mm	75 mm	30 mm	63 %

fine motor hobby and do not play a musical instrument (60%). None of the subjects has circulatory disorders or arm, hand, or finger limitations, and the majority are non-smokers (96.70%).

Test Person Study

In the test-person study, the participants have to perform two parallel tasks, so the experimental setup consists of two components (see Figure 2). Similar to a surgery, the subject has to hold a surgical instrument in the form of a wire eyelet over a rod as still as possible in the minimally invasive laparoscopic operating field with their dominant hand. Any contact with the edge of the eyelet (1) is recorded and is judged an error. The experimental setup is adjusted to the dominant hand of the participant. At the same time, as a secondary task, the subject has to perform various adjustment tasks with a virtual slider in the air (2).

The information transfer of the tactile perception channel is examined with regard to differences in the tactile scale characteristics. For this purpose, different scale characteristics representing an "increase" or a "decrease" over the feedback intensity are played back to the subject as part of the secondary task. The subject's task in the first part of the study is to distinguish between an "increase" or "decrease" in feedback intensity (see Table 1). The scale can be run several times. If the subject is sure about the scale characteristic, he is

Figure 2: Experimental setup with the main task (1) and the secondary task (2).

asked to set the scale to position 6. Subsequently, the questions regarding the recognition of the scale characteristics as well as the classification regarding the indication of an "increase" or "decrease" are answered on the basis of a 7-step Likert scale. The scale ranges from 0 (completely unsuitable) to 6 (very well suited). The mental load of the adjustment task according to Borg (DIN EN ISO 9241-420, 2011) is also queried. In the second part of the study, the subjects are asked to evaluate the tactile features with regard to their suitability for the coding of a "middle of a scale" or a "preferred scale value". Analogous to part 1, this subtest is also performed under the parallel execution of the main and secondary task. Therefore, the tactile features from Table 2 are tested. For this purpose, the subject is asked to evaluate the tactile features with respect to its character to assign it to the coding of a "middle" or a "preferred value". The subject can move over the scale several times. If the subject is sure about an assignment, he is asked to adjust the scale position directly to the right of the tactile feature and then rate the suitability for the representation of a "preferred value" or a "middle" using a 7-point Likert scale. The scale is evaluated using a 7-step Likert scale by means of pairs of opposites (0 "completely unsuitable" and 6 "very well suited"). In addition, the mental load according to Borg (DIN EN ISO 9241-420, 2011) of the adjustment task is also queried.

RESULTS

Figure 3 shows the recognition rate of the scale characteristics for the "increase" and "decrease". Figure 3 reveals that the correct recognition of the scale characteristics becomes more difficult as the difference between the start and end values of the intensity decreases. The best recognition rate of 100% achieve the scale characteristics V1.1 and V1.5. The lowest recognition rate achieves scale characteristic V1.8.

The same is reflected in the subjects' evaluation of the suitability of the scale for the indication of an "increase" or "decrease" in Figure 4. With a decreasing difference between the start and end values, the evaluation of the suitability decreases. The best rating is given to scale characteristic V1.1 with Ø = 4.60. The worst rating in terms of suitability for indicating an

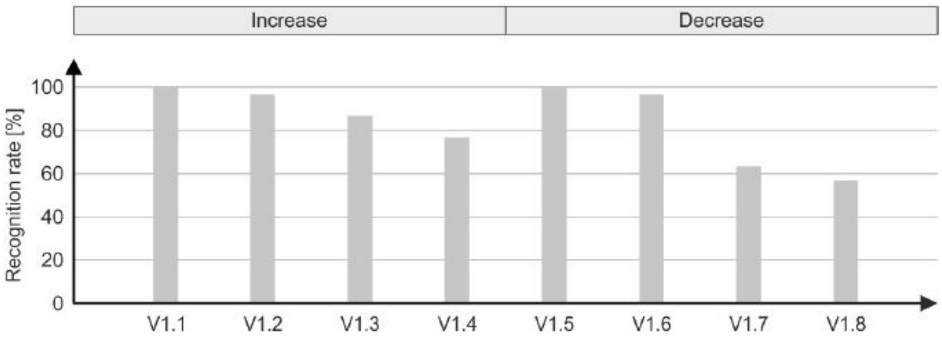


Figure 3: Recognition rate of the tactile scale characteristics increase or decrease.

"increase" is given to scale characteristic V1.4 (Ø = 2.67). For the indication of a "decrease" according to Figure 4, the scale characteristic V1.5 (Ø = 4.23) is best. The scale characteristic V1.8 (Ø = 1.50) is rated worst. This is also confirmed by the inference statistical investigation. Since a normal distribution can be negated, a Friedman test with subsequent Dunn-Bonferroni correction is performed for the evaluation of the scale characteristics with respect to an "increase" ($X^2(7) = 149.690$, $p < 0.001$, $n = 30$) and a "decrease" ($X^2(7) = 145.845$, $p < 0.001$, $n = 30$). Regarding the evaluation of an "increase", a significant difference is evident between the scale characteristics V1.1-V1.4 ($z = -3.320$, $p = 0.025$, $n = 30$). Regarding the "decrease", the evaluation differs highly significantly for the scale characteristics V1.5-V1.8 ($z = -4.269$, $p < 0.001$, $n = 30$) and very significantly for the scale characteristics V1.6-V1.8 ($z = -3.584$, $p = 0.009$, $n = 30$).

Figure 5 shows the mental load ratings of the scale characteristics. Scale characteristic V1.1 experiences the lowest mental load when indicating an "increase" (Ø = 2.90). The worst evaluation reaches V.1.4 with an average

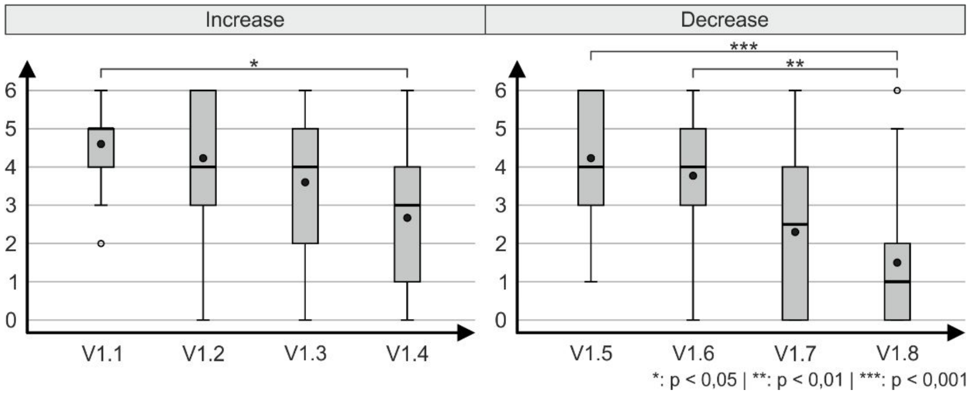


Figure 4: Evaluation of the suitability (0 "completely unsuitable" to 6 "very well suited") of the scale characteristics for coding an "increase" or "decrease" along a tactile scale.

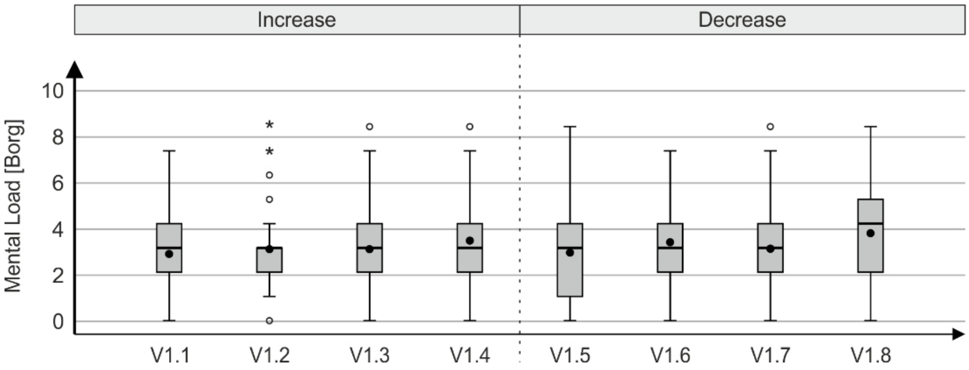


Figure 5: Evaluation of mental load according to DIN EN ISO 9241–420 (2011) in terms of coding an increase or decrease.

evaluation of Ø = 3.50. For the purposes of indicating a "decrease", the smallest mental load for scale characteristic V1.5 (Ø = 2.98) is omitted, whereas the mental load for scale characteristic V1.8 (Ø = 3.82) is evaluated as the strongest.

The evaluation of the tactile scale characteristics for coding a "middle" or a "preferred value" is shown in Figure 6. Based on the boxplot diagrams, it can be seen that scale characteristics with a change in the scale spacing (cf. V2.3 or V2.4) are on average better evaluated than a sole change in the feedback intensity in a positive or negative direction (cf. V2.1 or V2.2). For the coding of a "middle" on a tactile scale, tactile feature V2.4 (Ø = 3.43) is the most suitable, followed by V2.3 (Ø = 3.20) and V2.7 (Ø = 3.10). In terms of coding a "preferred scale value", tactile feature V2.3 is the most suitable, with an average rating of Ø = 4.13. The least suitable is tactile feature V2.2 (Ø = 1.70). It can be seen that the tactile features are generally rated somewhat better for coding a "preferred value" than for coding the "middle of a scale".

There is no normal distribution in the test data. Therefore, for the evaluation, a Friedman test for the "middle" ($X^2(7) = 44.046$, $p < 0.001$, $n = 30$) and a Friedman test for the "preferred value" ($X^2(7) = 43.395$, $p < 0.001$, $n = 30$) with a subsequent Dunn-Bonferroni post-hoc test are performed for the inferential statistical examination of the data in each case. Statistically significant differences in the evaluation of the scale characteristics for the coding of a "middle" are mainly present with regard to tactile feature V2.2. Thereby, tactile feature V2.2 becomes very significant (cf. V2.2-V2.6 ($z = 3.768$, $p = 0.005$, $n = 30$)) and highly significant (cf. V2.2-V2.3 ($z = -0.796$, $p < 0.001$, $n = 30$), V2.2-V2.4 ($z = -4.928$, $p < 0.001$, $n = 30$), V2.2-V2.5 ($z = -4.322$, $p < 0.001$, $n = 30$), and V2.2-V2.7 ($z = 4.954$, $p < 0.001$, $n = 30$)) scored worse. To point out a "preferred value" on a scale, statistically significant differences are also present with respect to tactile

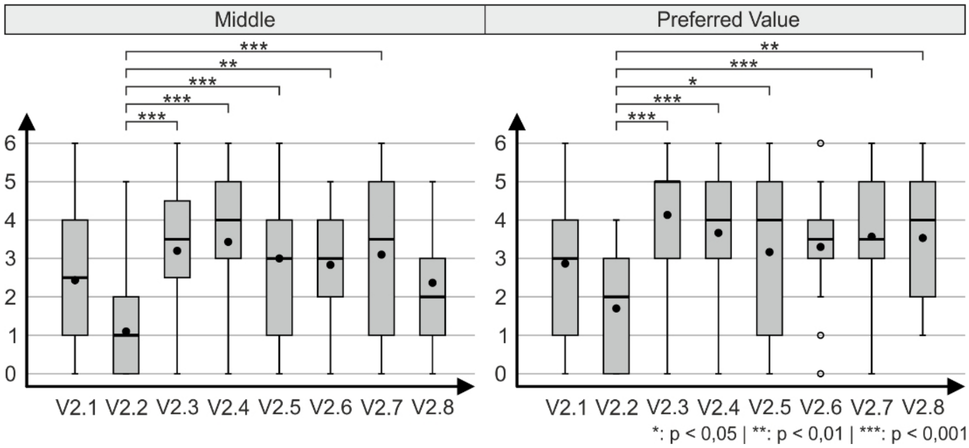


Figure 6: Evaluation of the suitability (0 "completely unsuitable" to 6 "very well suited") for indicating a middle or a preferred value.

feature V2.2. The rating of coding feature V2.2, is compared to V2.5 significantly ($z = -0.268$, $p = 0.030$, $n = 30$), compared to V2.8 ($z = -3.926$, $p = 0.002$, $n = 30$) very significantly, and compared to V2.3 ($z = -5.850$, $p < 0.001$, $n = 30$), V2.4 ($z = -4.348$, $p < 0.001$, $n = 30$), and V2.7 ($z = -0.322$, $p < 0.001$, $n = 30$) highly significantly worse.

The evaluation regarding the mental load for the coding of a "middle" or "preferred value" is shown in Figure 7. In the context of this study, coding with tactile feature V2.3 (Ø = 2.93) exerts the lowest mental load. The strongest mental load for coding a "middle" or a "preferred value" is exerted by tactile feature V2.2 (Ø = 3.68). The mental load caused by coding an increase in intensity (V2.1) or a decrease in intensity (V2.2) is perceived as more stressful than that caused by changing the scale spacing (cf. V2.3 or V2.4).

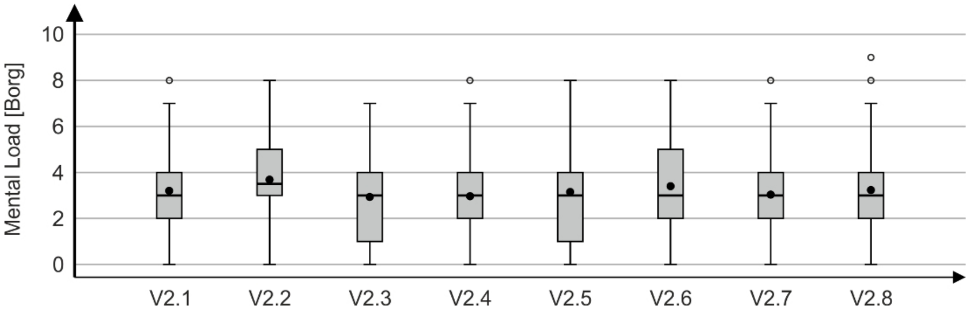


Figure 7: Evaluation of mental load according to DIN EN ISO 9241–420 (2011) in terms of coding a middle or a preferred scale value.

DISCUSSION

The results of the investigation show that the coding of an "increase" or "decrease" is possible with a linearly changing feedback intensity in the scale characteristic of a discrete tactile scale (cf. Figure 4 V1.1 and V1.5). Based on the changing intensity, it is possible to differentiate between an "increase" and a "decrease". Focusing on the perception threshold, both "increases" and "decreases" are detected by more than 50% of the subjects. It is also evident from the tests (cf. Figure 3) that an "increase" or "decrease" with a smaller difference between the start and end values is perceived worse. A smaller difference in feedback intensity between the scale points is also classified by the subjects as less suitable. Whether an even steeper increase or decrease in feedback intensity would have led to better results needs to be investigated in more detail in future studies. For further studies, other scale characteristics such as a quadratic or exponential increase or decrease of the feedback intensity would be of interest. Furthermore, another coding possibility could be the scale distance. The coding of an "increase" or "decrease" via a condensing or widening scale spacing could be investigated in further studies. The coding of a "middle" should be done by means of a sharp change in the scale spacing. According to this study, an asymmetric change of the scale spacing is best (see Figure 6 V2.4). The coding of a middle via a sole increase or decrease of the feedback intensity unsettles the subjects, which is why the suitability of this is considered worse than a single increase of the scale spacing. The combination of a change in scale spacing and a change in feedback intensity also does not lead to a better result. The worst rating is given to the sharp decrease of the feedback intensity (cf. Figure 6 V2.2). Due to the sharp decrease in feedback intensity, the scale position is hardly perceptible by the subjects, which results in an uncertainty regarding the recognition of the tactile feature. For the coding of a "preferred value" of a discrete tactile scale, the coding via a symmetric change of the scale spacing is most suitable (cf. Figure 6 V.2.3). A sole sharp decrease of the feedback intensity is poorly perceived by the subjects, analogous to the coding of a "middle", and leads to an uncertainty about whether they have recognized the tactile coding feature. Also, combining the sharp change in intensity with the sharp change in scale spacing results in a worse result compared to the sole change in scale spacing. The mental load of the tactile coding features with a change in the scale spacing is rated lowest by the subjects and is stronger when combined with a sharp change in intensity or a sole change in intensity. Accordingly, coding via a sharp change in feedback intensity requires greater attention from subjects. Nevertheless, there is a need for further research on the finer differentiation of the change of the scale spacing.

CONCLUSION

It could be shown that it is possible to transfer information such as an "increase" or "decrease", the coding of a "middle", as well as the coding of a "preferred value" via the tactile feedback of a discrete scale in the air. Regarding the coding of an "increase" or "decrease", further research should be conducted regarding the shape of the scale in addition to a linear increase or decrease. The change in the scale spacing for the coding of a "middle" as well as for the coding of a "preferred value" is better perceived and the suitability is better evaluated by means of this coding possibility than by a sole intensity change. For tactile coding of a "middle" or a "preferred value", further studies with more differentiated subdivisions of the scale spacing change as well as feedback intensity changes in a positive direction should be conducted. Lowering the feedback intensity to indicate a "middle" or a "preferred value" should be discarded according to this study.

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