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Validation of ergonomic criteria of a cooling vest for deep and ultra-deep mining

Valérie Tuyêt Mai Ngô, Sylvie Nadeau *, Stéphane Hallé

École de technologie supérieure, Montreal, QC, Canada

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ABSTRACT

The high levels of heat and humidity in ultra-deep mining raise issues regarding the occupational health and safety of miners as well as productivity. Miners could wear a cooling vest to reduce heat strain, but it would need to be properly adapted to the constraints and requirements of deep and ultra-deep mines. This article examines the first phase of a validation of a previously proposed usability matrix composed of 16 ergonomic criteria via expert elicitation (from both the academic and mining sector) and lab experiments with human participants in a controlled environment. A questionnaire was used to ask experts to prioritize the criteria and determine which of these should be combined, rejected or added. Laboratory participants were asked to execute typical mining movements to assess a number of criteria for two different cooling vests (one prototype and one commercially distributed) and complete a questionnaire containing a 6-point Likert scale for five criteria: fit, comfort, ease of movement, usability and design aesthetics. Eight experts and ten laboratory participants completed their respective questionnaires. The usability matrix was improved and structured into a mind map representing all relevant criteria and their relationships. This mind map will need to be tested further with experts and miners to ensure and complete its scientific validity.

1. Background

Miners who work in deep and ultra-deep mining conditions (more than 2 km underground) are faced with thermal constraints that are difficult to mitigate. Temperature and humidity rise (10 °C per km of depth) due to air auto-compression and the use of mine water to wash walls for scaling or mining operations (Ngô et al., 2016). Miners can suffer from heat illnesses (Donoghue, 2004) and it is sometimes not even necessary to be at deep mining levels to be in a situation where heat strain is a factor. Ngô et al. (2017) measured temperatures of 35 °C and 99% relative humidity at depths of 1800m.

Heat stress can be the cause of accidents and injuries as well as diminished physical performance and productivity (Maurya et al., 2015; Donoghue, 2004; Xiaojie et al., 2011). Studies show that cognitive performance (Jay and Kenny, 2010; Leveritt, 1998) and heat (Lao et al., 2016) might impact age groups differently. Age can be a significant consideration, as shown by data from the Mining Industry Human Resource Council of Canada, indicating that 45% of the mining labor workforce (MIHRC, 2018) is between 45 and 64 years old. Multiple health and safety organizations such as the Mine Safety and Health Administration (USA), Workplace Safety North (Ontario, Canada), the Department of Mines, Industry Regulations and Safety (Australia) have shown interest and concern regarding heat stress in mining environments and the prevention of accidents.

Air conditioning is, to some extent, helpful, but it is expensive in the long term and does not effectively reach the end of the galleries (face of the mine) where the miners are working. It is believed that personal protective equipment, such as a cooling vest, would more efficiently help to alleviate the thermal strain of miners. Kenny et al. (2011) tested an ice cooling vest in controlled hot and humid conditions and found that it could reduce the level of thermal strain and increase exercise time. Participants wore the vest under a nuclear chemical suit while exercising on a treadmill in 35 °C and 65% relative humidity conditions. Similarly, Guo et al. (2017) developed a prototype for construction workers, which they tested in a controlled environment (37 °C, 60% relative humidity) while exercising on a treadmill. They noticed an increase in the duration of exercise and reduced thermal strain of their participants. The prototype vest developed by Al Sayed et al. (2019)also showed improvements in terms of heart rate, internal body temperature, perceived well-being, and thermal comfort at 30 °C and 60% relative humidity while their participants were exercising on a stationary bicycle.

Nonetheless, transferring a cooling garment from laboratory conditions to real work conditions is not so simple. The work activities differ and various additional constraints come into play, e.g., terrain inclination, task duration and external load. Drain et al. (2016) discussed such differences in the context of load carriage for military personnel and firefighters. To the best of our knowledge, no existing portable

* Corresponding author. Mechanical Engineering Department, École de technologie supérieure, Montreal, QC, H3C 1K3, Canada.
E-mail address: sylvie.nadeau@etsmtl.ca (S. Nadeau)

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cooling technology is perfectly suited to deep and ultra-deep mining environments (Al Sayed et al., 2016). In an effort to fill the gap, Ngô et al. (2017) proposed a first version, consisting of a 'usability' matrix of ergonomic criteria in designing a cooling vest for deep and ultra-deep mining. However, this matrix has yet to be validated.

To this effect, Lewis (2014) defines two major concepts of usability: 'summative' and 'formative'. The first is similar to the ISO 16982 (International Organization for Standardization, 2002) standard in which a product is useable when it is used by the intended users with effectiveness, efficiency and satisfaction, whereas the second is based on the "absence of usability problems". Hence, the usability matrix for a 'yet-to-be-created' cooling vest falls under the 'summative' type of usability, as problems cannot be quantified at this stage of the research and development process. Therefore, the current study's main objective is to validate the previously proposed matrix of criteria (Ngô et al., 2017) using triangulation (Leedy and Ormrod, 2016). Two sources of data were already used in the previous study. Literature data describing the occupational constraints and requirements of miners and corroborating data obtained through field observations and directed interviews with miners (Ngô et al., 2017). The current study will provide the third part of the triangle, validation data obtained from experts and laboratory participants. It was determined that experts deem effectiveness and design aesthetics as being two well-defined and opposite priorities and participants contributed a discriminative opinion on the importance of the ease of movement criteria. A mind map of the usability criteria was also developed and proposed.

2. Methodology

To achieve the initial objective of validating the usability matrix, a two-part method was used, namely, expert elicitation and a laboratory study. Expert elicitation was chosen since no model or existing data was available for such a matrix (O'Hagan et al., 2006). The laboratory study was conducted in a controlled environment with human participants from a university setting. The project being at a technology readiness level of 6, this was deemed sufficient for the purpose.

Both protocols were submitted to the Ethical Committee of *École de technologie supérieure* and approval was obtained in January 2016.

2.1. Expert elicitation

Two types of experts were contacted for the elicitation: university experts (according to their current field of research and having experience in occupational health and safety (OHS)), and OHS professionals with a work experience of a minimum of 15 years in the mining sector. The experts were first contacted by telephone, and if that failed, an email was sent. A consent form was sent to voluntary participants along with a questionnaire, which they could either complete on their own (within three weeks) or by telephone.

The questionnaire was created to determine the following: the expert's field of expertise, the expert's perspective on the priority of the criteria and whether the expert deemed any criteria redundant, superfluous or missing. The definitions of the criteria were listed at the beginning of the document (Ngô et al., 2017). The experts were to compare the 16 criteria in pairs and indicate which of the pairs they would prioritize. Each criterion could have between zero checkmarks (if they were never prioritized) and a maximum of 15 checkmarks (if they were consistently picked over the others). The results were then analyzed using linear opinion pooling while taking into account different factors: field of expertise, university or mining background, position of the criterion - overall and for each expert. A mathematical aggregation was used because behavioral aggregation was not realistic due to the geographical locations of the experts. Upon completing the questionnaire, the experts had to explain their answers based on the following three questions:

- Are there any criteria that you would combine and why?
- Are there any criteria that you would remove and why?
- Are there any criteria that are not currently in the matrix and why would you add them?

2.2. Participant validation

Participants were recruited via posters announcing an information meeting that explained the parameters of the research and answered any questions. Potential participants were then given a consent form and invited to contact the researcher if they chose to participate. All participants recruited were male and this was deemed acceptable given that the majority of Canadian miners are male. Only 4% of underground miners in Canada are female (WIM Canada, 2010).

During the validation tests, participants wore two different vests in two separate tests, a cooling vest prototype using atmospheric discharge of liquid CO_2 as a cooling mechanism (Al Sayed et al., 2019) and a phase-change garment (PCG), which is currently commercially available. A three-week interval was planned between the two tests to ensure that the participants had an objective perception of each vest, as the goal of this study, was to validate the usability matrix and not assess any direct comparison between the two vests. The subject's age, weight, height and measurements of the torso and neck with and without the vests were noted during the tests.

The participants were also asked to perform typical movements that can be associated with deep and ultra-deep mining work (MIHRC, 2009): standing, walking, crouching, kneeling, extending arms, turning the head or trunk and using a scaling bar of similar length and weight as those used in mines. Other criteria tested were adjustment, usability, comfort and design aesthetic. The participants' movements were recorded using two GoPro Hero 3 + Silver Edition cameras (GoPro, USA). The researcher sometimes asked the participants to turn for certain movements to capture all angles.

Participants were asked to answer questions about each criterion using a Likert scale, that is, a psychometric scale that helps to determine the level of agreement or disagreement with a statement, and to comment their assessments on a voluntary basis. Lee and Paek (2014) observed that 4 to 6-point scales are similar in reliability and that reliability decreases the fewer the response categories. Chang (1994) found that the reliability of a 4-point versus a 6-point scale may depend on empirical settings. Preston and Colman (2000) suggested that a 4-point range and below performs relatively weak in terms of reliability, validity and discriminating power while these elements were higher for scales containing five to seven categories. For this reason, the scale used in this study had three levels of disagreement and three levels of agreement. Since a neutral opinion would provide no additional information about the usability of the matrix, the option was removed, resulting in a 6-point Likert scale. Participants were asked to complete the scale after each step of the test. For example, after putting on the vest, the participant would complete the adjustment category in its entirety. The scales were analyzed using the same linear opinion pooling method as for the experts. Unfavorable opinions were investigated using the comments of the participants as well as video recordings.

3. Results

3.1. Expert elicitation

3.1.1. Sampling

In total, 8 experts participated in the study. The initial objective was to consult only persons having expertise in personal protective equipment. However, the number of experts in this field in Canada is quite limited so the requirement was extended to all OHS experts.

There was no conflict of interest between the experts surveyed and our research.

3.1.2. Hierarchy of criteria

Experts' prioritization showed that efficiency was prioritized above all other elements, with 101 votes and a rank of 2.8. The design aesthetic was the last priority, with only 4 votes and a rank of 15.7 (out of 120 possible votes and ranking from 1 (top) to 16 (last)). Results for the other criteria did not tend to converge, as multiple criteria had similar rankings and numbers of votes (Ngô et al., 2019).

3.2. Participant validation

3.2.1. Sampling

In total, 10 male participants were selected to test two different cooling vests in a laboratory setting. In both cases, the cooling functionality of the vests was inactive during the tests. Moreover, since the participants were not doing strenuous exercise, the cooling function might have influenced the results pertaining to comfort. The personal characteristics of participants are presented in Table 1.

Body measurements were taken using a soft tape measure (Tilley and Henry Dreyfuss Associates (2002). It should be noted that the neck and back lengths were direct body measurements, whereas the vests did not cover those body parts; thus, they were not re-measured.

3.2.2. Perception about the vests and usability matrix

The answers obtained from the Likert scale were summarized in the same way as with the expert elicitation, using mathematical aggregation. The overall results are presented in Table 2. The following are examples of questions asked to the participants, as specified in the questionnaire:

- Fit: 'Is the vest fitted at the [part of body]'?
- Ease of movement: 'I had no problem [action] while wearing the vest.'
- Comfort and aesthetic design: 'Is the vest comfortable? I would wear the vest at work; I like the look of the vest.'
- Usability: 'Is it easy to use, to manipulate the vest in this way?'

As for fit, discordance arose at the waist and neck, which were either too large or too tight. In the ease of movement category, five out of ten users had difficulty in performing the arm movements as the vest's design restrained them. The movement of the shoulders was not comfortable when trying to use a scaling bar in a forward pushing motion. Comfort converged with only one participant disliking both vests equally. As for usability, one vest had worse results in terms of putting it on, removing it and manipulation compared to the other. The results indicate that the questions were sufficiently discerning.

Table 1
Personal characteristics of participants.

	Age (yrs.)	Weight (kg)	Height (cm)	Body Mass Index
Min	22.0	55.0	164.0	18.6
Max	54.0	105.0	187.0	35.1
Mean ± Standard deviation (SD)	30.2 ± 8.7	78.8 ± 13.2	175.8 ± 7.2	25.6 ± 4.5

Table 2
Participants' answers (in Mean ± SD) for each matrix criteria.

	Fit	Ease of Movement	Comfort	Design Aesthetic	Usabilit
Mean ± SD	4.8 ± 1.2	5.3 ± 0.8	4.5 ± 1.1	4.3 ± 1.5	4.8 ± 1
#of questions/ category	4	15	1	2	4 or 5 depend on vest type

3.3. Mental model development

3.3.1. Experts

Experts are repositories of tacit knowledge, which "is subjective, personal and context specific" (Ford and Sterman, 1998). When attempting to determine which criteria should be combined and which are superfluous or missing, typically experts consult their acquired knowledge and refer to their mental models. Mental models can be valuable tools to conceptualize systems and transmit information from experts to workers, as stated by Nadeau et al. (2012) (see Fig. 1).

In the work of Fatisson et al. (2013), the researchers hierarchized a network of elements of risks, finding reciprocal and cause-effect relationships between different elements. In our case, the experts proposed to combine, remove or add criteria because they felt there was a relationship between them. The analysis of all the comments culminated in the model shown in Fig. 2, with the new criteria introduced by the experts appearing in grey. Four types of relationships were identified by analyzing the comments:

- Similarities (e.g., hindrance and snagging are similar) – represented by dotted double arrows.
- Inclusions (e.g., hindrance is a part of ease of movement) – represented by dotted boxes.
- Reinforcements (e.g., hindrance affects ease of movement) – represented by simple arrows.
- Dependencies (e.g., to be reliable in deep mines, a cooling vest must be both robust and easy to maintain) – represented by logical 'AND' doors.

Some criteria were not mentioned in relation to others, these included the mandatory criteria of back-end risks, conformity to laws and regulations, and cost. Acceptability, wearability, reliability, thermal and tactile comfort were all added to the mental model following the statements of the experts.

3.3.2. Corroboration based on laboratory participants' comments, videos and Likert scale answers

The opinions of the participants confirmed some of the experts' opinions and established other relationships. In Fig. 2, those relationships are represented by the orange dotted arrows.

- Fit having a reinforcing effect on ease of movement (e.g., if it fits well, I am able to move my shoulders more easily).

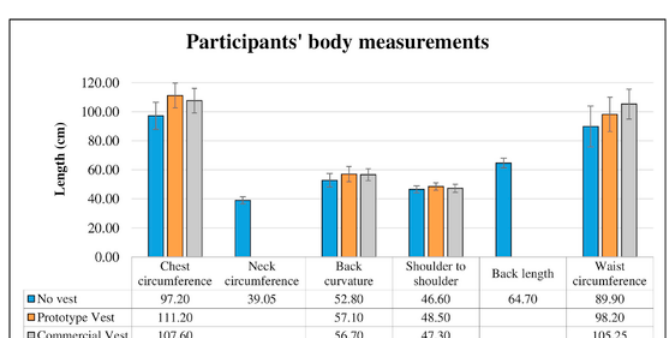

Fig. 1. Participants' body measurements (in Mean ± SD) with and without the vests.

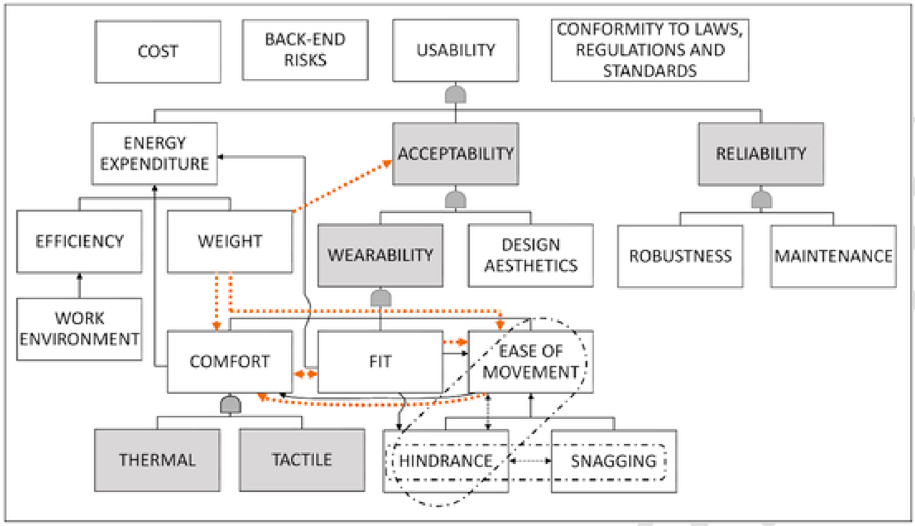

Fig. 2. Mental model of the usability matrix.

- Ease of movement having an influence on comfort (e.g., the vest hinders movement of the arms, with the fabric being scratchy and uncomfortable).

The new relationships that emerged included:

- Weight and ease of movement (e.g., vest weight limits my movements).
- Weight, comfort and acceptability (e.g., vest is heavy, I wouldn't wear it unless I had to).
- Fit and comfort (e.g., straps used to adjust the fit of the vest were said to be annoying, with the cooling function being inactive, the person wearing the vest was experiencing heat because the fabric was too tight and not breathable).

4. Discussion

4.1. Expert elicitation

The main difficulty in selecting experts throughout Canada was availability, as experts are in high demand and have a busy schedule. A self-administered questionnaire helped us retain experts, but might have lowered the quality of the responses (O'Hagan et al., 2006), while face-to-face or phone interviews might have enabled us to converge the priority of more criteria.

Ford and Sterman (1998) explain that a good expert elicitation includes three phases: a position phase where context and goals are explained, a description phase where the experts transform their knowledge into a useable form and a discussion phase intended to understand the description phase with the experts. While the position and description phases were for the most part achieved in this study, the discussion phase was not.

In terms of combining, removing or adding new criteria, experts rarely had concurrent opinions. Explanations indicated that some criteria relationships were unclear. For example, it was suggested that fit and comfort be combined given that one influences the other. However, they are not the same and can evolve independently (e.g., a vest can fit a body well but still be made of a scratchy material which makes it uncomfortable). This was confirmed by the participants' answers, which attributed a high score to comfort while having disagreements in terms of fit.

Regarding the removal of criteria, one explanation stated that some of the definitions were too general in comparison to others (e.g., efficiency, which is the sum of output on input is straightforward when speaking about a cooling vest compared to a working environment). Inclusion relationships as well as the mandatory conformity to laws, regulations and standards were stated as reasons to eliminate a criterion. While relationships between criteria were identified during the analysis of the explanations of the experts, none of the criteria were either combined or removed. All statements were evaluated and some precisions were added in criteria such as thermal and tactile comfort. The suggestion that visibility be added to the usability matrix was disregarded given that this criterion is already mandatory for miner's work garments in Quebec's regulations.

4.2. Participant validation

When comparing the data between the two sample populations (20 miners (Ngô et al., 2017) and 10 university participants in the current study), the most significant difference is the weight of the participants. Miners weighed an average of 20 kg more than the university participants while height was consistent between the two groups. The added bulkiness of the vest, which was present in both the prototype and commercially available cooling vest is an element to be considered in the design of personal cooling vests.

Only males were recruited for this study, in part to facilitate the recruitment process, which took place in a predominantly male environment (Science, technology, engineering and mathematics (STEM) environment: insuring recruitment diversity is a challenge) and also because there is a low percentage of females in the mining workforce (WIM Canada, 2010). This is not to say that female miners should not be consulted in the future nor that they would not benefit from the use of a cooling vest. To this effect, Watkins et al. (2019) highlighted significant differences in women firefighters, such as the lack of appropriate fit of a PPE as compared to men firefighters, thus making women potentially more at risk for injury and illnesses. This was not explored in this paper but could be part of future studies. As previously mentioned, this research was the third part of a triangulation. Given that the technology was at readiness level 6, assessment in a controlled environment was achieved.

4.3. Corroboration with other research

Chan et al. (2018) evaluated the usability of cooling vests in Hong Kong industries using a structural model with causal effects among three variables, cooling effect, ergonomic design, and usability. A

5-point Likert scale was used to evaluate multiple criteria: thermal sensation, wetness sensation, weight, freedom of movement, durability, overall comfort, convenience, acceptability, perceived effectiveness to protect from heat stroke and satisfaction. All their criteria, except for wetness sensation and durability, concurred with the criteria found in the mind map proposed in this paper.

In a previous study (Ngô et al., 2017), miners expressed concerns regarding the development of a new cooling vest. Many of those concerns were linked to the acceptability of the vest and the miners' ability to still be able to do their work. While all miners expressed their opinion that they would try a vest, the concerns about weight, comfort, hindrance, snagging and ease of movement all influenced the acceptability of the vest. This validates the acceptability branch of the mind map. When Bach et al. (2018) interrogated emergency first responders about implementing a cooling vest, cost, effectiveness and employee comfort/durability were some of the barriers mentioned, which happen to be criteria also found in our mind map. Finally, Bitkina et al. (2020)found differences between user experience and usability, one seemingly being a subset of the other with user experience having broader scope and criteria. Thus, the actual experience of wearing a vest designed using the usability mind map might uncover more criteria in the future.

5. Conclusion

The usability matrix was validated and converted into a mind map. Effectiveness of the vest was determined as being the main priority for the development of a cooling vest. This is logical considering the hot and humid environment in which it will be used.

To achieve a definite mental model of the usability matrix, further research is needed. First, it will be important to validate that the developed model is faithful to the experts' mental model to clarify whether further information must be added and to ensure the opinions converge towards the same result, which is usually the last step of expert elicitation. Second, because the participants were not the final users of the cooling vest, it will be important that miners, as the primary wearers of the future cooling vest, should be consulted. This should help achieve a work-ready usability matrix. More research is needed to ensure the resulting cooling vest is also appropriate for female miners. In the long term, this research could also be used to design cooling vests for more vulnerable populations and other heat affected industries such as construction, agriculture, foundries, and firefighters, to name a few.

CRediT authorship contribution statement

Valérie Tuyêt Mai Ngô: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Sylvie Nadeau:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Stéphane Hallé:** Resources, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

No conflict of interest was reported by the authors.

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