Evaluating the usability of a prototype gesture-controlled illuminative textile

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Abstract

In the field of human-computer interaction (HCI), recent years have witnessed an increasing interest in smart textiles with gesture recognition functions. This paper reports usability evaluations of a prototype gesture-controlled illuminative textile developed by the authors. This is an interactive woven POF textile system with computer vision-enabled mid-air gesture recognition. For the usability test, 25 participants (11 males and 14 females) aged between 19 and 56 (M = 30.85, SD = 10.8) were randomly recruited. The study was conducted by the means of the user experience questionnaire (UEQ) and the system usability scale (SUS). Results show that participants responded positively to our gesture-controlled illuminative textile in terms of its attractiveness, perspicuity and stimulation but were less positive about its efficiency. The results will be used to make targeted improvements to the existing product design.

Keywords: gesture-controlled illuminative textile, hand gesture recognition, polymeric optical fibre, usability test.

Introduction

Rapid technological advances increasingly rely on the application of artificial intelligence (AI) to create smart devices and services. Research indicates that there is market demand for gesture recognition intelligent textiles based on computer vision, which is an important feature of AI. The market value of the gesture recognition and touchless sensing sector is projected to rise from USD13.6 billion in 2021 to USD37.6 billion by 2026 (MarketsandMarkets, 2021).

Hand gestures are simple and effective means of communication and are considered to offer an intuitive mode for human-computer interaction (Chmurski, Zubert, Bierzynski, & Santra, 2021; Zhang, 2021). Electronic textiles (e-textiles) that can adapt to and interact with users via gesture recognition possess the potential for a range of applications.

With regard to e-textiles for daily use, unobtrusive integration of electronic components and the conductive material is key in achieving the sensing or actuating functions. Smart textiles interact with users by proximity sensing, and conductive flexible textiles provide an excellent medium for this interaction. With the aid of conductive yarn, the interactive e-textiles can be actuated by the proximity of users' hands (Cheng, Kim, & Vertegaal, 2011; Olwal, Starner, & Mainini, 2020; Tan, Bai, Ge, Shao, & Chen, 2019; ten Bhömer, 2021).

In contrast with the cited examples, the gesture-controlled illuminative textile developed by the authors is distinct in that it achieves interaction via mid-air gestures without the need for physical contact and proximity (Tan, Shao, Lam, Toomey, & Ge, 2021). The gesture-controlled illuminative textile system is comprised of a polymeric optical fibre (POF), computer vision via an integrated camera, and a minicomputer. The success of an e-textile, as with most products, is decided by user experience (UX), which is defined as the perceptions and responses of users to a product, system, or service (International Organisation for Standardization, 2019). Users' perceptions include emotional, cognitive, or physical reactions to the use of a product. UX is currently a key factor in establishing the quality of a product or service (Schrepp, Hinderks, & Thomaschewski, 2014). Evaluation of the prototype designed by the authors is essential for interactive system development. The feedback gained from the user experience tests is crucial to the further development of the system and the enhancement of its function.

The developed gesture-controlled illuminative textile is activated by hand gesture recognition via a micro camera and minicomputer. Illumination varies in accordance with specific hand gestures, the illumination is provided by the LEDs which are coupled to the POF bundles woven into the textile. The touch-less gesture recognition function was designed and fabricated using an open-source AI model. The interaction between user and system is essential to the success of final product development. This paper reports usability evaluations of a gesture-controlled illuminative textile developed by the authors (Tan et al., 2021). The textile was designed to be applied in everyday HCI environments, and so the sample group of 25 adults was recruited randomly. Participants were asked to complete user experience questionnaires (UEQ), and evaluation utilized a system usability scale (SUS).

Development of interactive gesture recognition textiles

The past decade has witnessed numerous attempts to improve the functionality of interactive products to advance the interaction between user and system. Various interactive e-textiles have been developed by embedding electronic components and circuits within conductive textile materials to achieve the functions of sensing and actuating (Gowrishankar, Bredies, & Ylirisku, 2017; Paradiso & De Rossi, 2008). Other e-textiles are activated by physical contact with the material to achieve interaction between users and the system.

A number of existing interactive e-textile products may be seen as innovative in terms of their design, development and functionality. Such products make use of conductive yarns inside the textile structure to realize a particular function. The Music Sleeve, for example, designed by a research team at Aalto University, Finland acts as a wearable controller of a mobile device for playing music (Gowrishankar et al., 2017). By moving a metallic coin inside the conductive part of the knitted tubular, a music player is triggered. Another example is the crocheted spherical Soft Radio (Gowrishankar et al., 2017), in which volume adjustments and channel selection are controlled by twisting the loop on the top of the radio to make contact with different conductive elements of the textile sphere. These two examples are touch-based gesture-interactive e-textiles with shape deformation used to actuate audio and music by bringing the conductive materials into contact, thus completing the electronic circuit. The intrinsic softness of textiles means that electronic components can be embedded within a range of fashion and lifestyle products.

In fact, the human body is a good conductor, and apart from shape deformation, this means that interactive e-textiles can be actuated by touch. An example of a touch-sensitive material is the Lumalive e-textile displays on T-shirts (Cheng et al., 2011), which is based on the location-tagged Universal Resource Indicator (URI) of touch-sensitive Lumalive shirts. Participants play a game involving a chaser and two players. The goal for the chaser is to press the specific touch- sensing area on the shirts of two players so that a token appears on the players' shirts. However, the token shifts from one player to another player when the chaser is approaching and gets within close proximity to the token-wearing player. This gaming design makes use of a touch-sensitive function in the e-textile to achieve interaction between the textile and the players.

I/O Braid is an interactive cord which functions through proximity sensation with the aid of braided conductive yarns and fibre optic visual feedback (Olwal, Moeller, Priest-Dorman, Starner, & Carroll, 2018; Olwal et al., 2020). The gesture recognition pipeline can be integrated, using a repeating braiding topology, by embedding fibre optic strands to achieve real-time visual feedback. The repeat detection and light matrices provide an innovative improvement in interactive devices. I/O braid functions like a remote control but in textile form, which may be applied to in-line headphone controls with high speed signal transmission. By twisting the I/O braid, volume may be adjusted and playing or pausing music is controlled by tapping.

Tactile Dialogues is an interactive e-textile pillow with a vibrating function that is activated by hand movements. It is formed by soft cotton fabrics in a knitted structure with conductive yarn stitching to provide sensation. Vibration is generated by a motor embedded in the pillow and when users touch the conductive yarn on the pillow, several levels of vibration are produced. This product is designed for patients suffering from dementia to encourage communication between users and their family members (ten Bhömer, 2021). The pillow is programmed with mirroring vibrating patterns when touched at opposite ends. This motivates the user to mimic and follow the contact gestures on the pillow made by the family member or caregiver at the other end. Dementia patients and their family members are able to participate in a collaborative sensory stimulation process beneficial to the patients.

Levi's Google Jacquard is an example of a product designed outside of the textile industry but which provides a novel interactive garment enabled by a touch interface system (Kaley, 2019; Levi's & Google, 2017; Poupyrev et al., 2016). A component with a small size rigid controller is located and embedded at the cuff to sense touch. The jackets allow access to digital services via the touch controls located at the sleeve cuff of the woven denim jackets. The controls synchronize wirelessly with smartphones and the commands can be enabled by simply tapping or swiping the jacket sleeve to play music, get directions via navigator, make calls, read incoming text messages and take photos.

The interactive e-textiles just described are activated by direct contact with the conductive materials or sensing components. In direct touching, a response is obtained within a second. By contrast, the AI textile system achieves interaction via mid-air gestures without the need for physical contact or proximity (Tan et al., 2021). The gesture-controlled illuminative textile system described here is comprised of a POF textile, computer vision via an integrated camera, and a minicomputer.

The creation of a computer vision-based prototype capable of recognising 22 numerical and emotive sign gestures. Innovative gesture recognition textiles allow users to interact without physical contact. A detachable micro-sized camera module is inserted into the channels of a woven, double-layer POF fabric. Hand gestures are captured in real-time for cloud computing. The hardware and software systems for the interactive system of gesture recognition textiles are developed. The Raspberry Pi 4B portable minicomputer is used as the processor. An open-source deep-learning classification model from Baidu Cloud analyses and recognises photos of real-time gestures transmitted over a Wi-Fi connection. Common power bank is used as the power supply for the interactive system. Users can control the colour changes of illuminative G-R textiles by posing basic numerical and emotive symbol movements in the mid-air.

Compared to direct contact e-textiles, contactless ones respond more slowly since gesture recognition entails a number of AI calculations running in the cloud simultaneously. Therefore, a few seconds may be needed for feedback, and stable internet and Wi-Fi connections need to be maintained throughout the process. However, in terms of hygiene, mid-air interactive e-textiles provide an innovative improvement that allows users to avoid touching fabrics directly. In a time of pandemic, this improvement is reassuring and minimizes cleaning maintenance. This is a novel mode of human-computer interaction, and so evaluation of the usability of the system is an essential step on the pathway to further development.

Usability Testing

The UX testing of this study is based on the User Experience Questionnaire (UEQ) and System Usability scale (SUS). The questionnaire is a commonly used tool to evaluate the user experience of a product or service (Laugwitz, Held, & Schrepp, 2008). In general, questionnaires are combined with other assessment methods to obtain an interpretable result. This is because some assessment methods provide only vague indicators in certain areas, while others investigate only a specific usability problem (Schrepp et al., 2014). Traditional methods usually looked at the usability criteria in a narrow sense and sometimes failed to capture practical and emotional aspects at the same time. According to Norman (2004), product design affects users on multiple levels: the visceral, behavioral, and reflective. This implies that practicality is as crucial as hedonic qualities, and both play a significant role in the overall user experience. The research method adopted in this study was designed to capture both the pragmatic and hedonic qualities of the product. As a result, the User Experience Questionnaire (UEQ) was adopted since it is comprehensive measurement of user experience and includes hedonic and pragmatic qualities (Schrepp et al., 2014). The UEQ offers a holistic approach that measures the usability of a product in six different aspects: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. It is an efficient and comprehensive measurement tool for usability testing with only 26 items to measure when compared to other user experience questionnaires such as SUMI and IsoMetrics which demand considerable user patience to address at least 50 statements. An additional benefit is that UEQ records the user's subjective perception of the product or system feature and the immediate impact on the user. Therefore, it avoids in-depth rational analysis and places the emphasis on capturing the immediate and spontaneous response of the user towards the product. The rationale here is that the interaction experience is easily forgotten or overlooked (Nielsen & Levy, 1994). Explicit evaluations carried out retrospectively are not always reliable but UEQ captures the immediacy of the user's experience.

The System Usability scale (SUS) was also used in this study. It was utilized as a standardized way to measure the perceived usability of the product in a quantitative manner. It provides a single reference score for participants' views of the usability of a product, system, or service. The scores provided by the SUS provide a comprehensive estimation of the usability of the gesture-controlled illuminative textile (Kortum & Bangor, 2013).

Throughout the development and testing process, the gesture-controlled illuminative textile underwent numerous changes as the development process progressed. Recording a SUS score at each stage of the development process allows the experimenter to compare each iteration using a standard tool. This provides a convenient and powerful way of deciding whether the textile in question is becoming more usable with each iteration. If negative trends are identified, corrective action can be taken in the early phases, while positive trends indicate that the process is headed in the right direction (Bangor, Kortum, & Miller, 2008).

The SUS, then, has attributes that make it stand out from other usability measurements. First, it is technology-agnostic; it is flexible enough to assess a wide range of interface technologies. Secondly, it can use by participants and administrators in an easy and quick manner. Thirdly, results can be easily understood by both professionals and laymen. Lastly, it is nonproprietary and hence cost effective (Bangor et al., 2008).

Usability test

Participants

A total of 25 participants (11 males and 14 females) aged between 19 and 56 (M = 30.85, SD = 10.8) were randomly recruited.

Procedure

The research information sheet, consent form, and questionnaire were introduced to the participants in advance of the usability test. The researcher explained the rationale of the study and acknowledged that they could question any part of the procedure and withdraw at any time without penalty of any kind. After the participants agreed and signed the consent form, each was invited individually into the experiment room. The researcher informed participants that the door would be closed for the duration of the test.

Participants were instructed to stand 30 cm in front of the gesture-controlled illuminative textile prototype hanging on the wall. They were then asked to lift their dominant hand up to the level of the camera integrated in the fabric. Researchers went through the procedure required to complete the usability test; a total of seven tasks. In each test, subjects were required to perform a hand number gesture. Each natural number has a corresponding color. Once the number gesture was displayed correctly and detected by the camera, the gesture-controlled illuminative textile changed color accordingly. The first three tasks were trials in which participants were required to gesture 1, 3, and 5 with their fingers. When performed correctly, the gesture-controlled illuminative textile displays red, green, and blue light respectively. This activity is designed to let participants get familiar with interaction with the textile.

The remaining four tasks required the participant to perform the hand number gestures 4, 6, 8, 9, they represent yellow (red light and green light mixing), magenta (red light and blue light mixing), cyan (green light and blue light mixing), and white (red, green and blue light mixing) respectively. The above colour mixing of light was based on the RGB colour model in the prototype gesture-controlled illuminative textile (Tan et al., 2021). Participants had to identify which colours appeared on the textile and record the colors in the questionnaire. The tasks were timed using a stopwatch but no time limit was imposed. Participants could raise questions if they faced difficulties or needed advice during the test. Questions and responses were recorded in detail. The researcher stopped the stopwatch when the participants had completed all tasks. Participants were then asked to fill out the remaining part of the questionnaire and, finally, were debriefed.

Environment

The usability test was conducted in an enclosed room with subdued lighting. Only the researcher and the participant were in the room during the test. A silent stopwatch was used to measure the amount of time needed to complete the usability test.

Gesture-controlled illuminative textile

The usability test was conducted on a prototype gesture-controlled illuminative textile (Tan et al, 2021) comprising 6 components: RGB LED light source, micro-computer, power supply, FPC interconnector and drive circuit for the LED light source. A micro-computer controls the illumination of the fabric via number gesture recognition. The computer was preprogrammed in advance to change the color according to the gesture detected. 7 colors were used in the usability test and each color was paired up a specific hand gesture. For the first part of the usability test, red, green, and blue were paired with the gestures depicting 1, 3 and 5 respectively. For the second part, gestures depicting number 4, 6, 8 and 9 were paired up with yellow, magenta, cyan and white respectively.

The micro-computer controlled the integrated camera to capture the hand gesture images from a distance of 30-100 cm. After the images had been captured, they were uploaded to an open-source artificial intelligence server for gesture recognition. The system recognized the gesture and the micro-computer changed the fabric color corresponding to the specific gesture by controlling the RGB light-emitting diode (LED).

Figure 1 Researcher interacts with the gesture-controlled illuminative textile prototype.

Questionnaire design

The questionnaire consists of two parts. The first part gathered basic demographic data (name, age group and gender). As the final product is targeted at the general public, the only criteria for screening was possession of a smart phone or tablet. The instructions of the usability test were also included in the first part of the questionnaire. The second part consisted of the learnability scale (a 10-point Likert scale), the system usability scale (SUS) and the user experience questionnaire (UEQ).

The SUS comprises 10 statements (for example: “I think that I would like to use this product frequently”) and measures a user's degree of agreement and disagreement to a statement on a 5-point Likert scale. Statements alternated between the positive and negative in an attempt to ensure that participants exercised caution when filling out the questionnaire. A final SUS score ranges from 0 to 100 could then be computed, where higher scores indicate better usability.

The UEQ comprises 6 scales (attractiveness, perspicuity, efficiency, dependability, stimulation and novelty) and 26 items (Schrepp et al., 2014). Attractiveness measures the overall impression of the product and addresses the question of whether users like or dislike the product. Perspicuity evaluates how easily a user can get familiar with or learn to use the prototype. Efficiency aims to determine whether users can solve the given tasks without undue effort. Dependability looks at whether the user feels in control throughout the interaction. Stimulation addresses the psychological effects on the user and measures how excited or motivated the user was when using the prototype. Lastly, novelty investigates whether the product is perceived as innovative and creative enough to catch the interest of the user. The attractiveness scale has 6 items while other scales have 4 items. Each item was represented by 2 terms with opposite meanings (for example: annoying/ enjoyable). The items are measured on 7-point scale from -3 to +3, where -3 represents the most negative answer and +3 the most positive answer, and zero indicates a neutral response. For each item, the order of the terms is randomised and half of the items of the scale commence with the positive term, while the other half begin with the negative term.

Results

The average time required to complete the whole usability test was 57.4 seconds with a standard deviation of 35.5 seconds. The learnability exercise recorded a mean score of 2.96 out of 10 with a standard deviation of 3.00. A low score means that the prototype is easy to use while a high score indicates the opposite.

Sauro (2011) created a grading system from the collected data provided by 241 industrial usability studies and surveys to create a curved grading scale (Figure 2) (Lewis & Sauro, 2018). We compared our data with the SUS norms data and found that our prototype has a mean score of 69.6 (grade C) and is in the percentile range 41-59.

Grade	SUS	Percentile range
A+	84.1 - 100	96 - 100
A	80.8 - 84.0	90 - 95
A-	78.9 - 80.7	85 - 89
B+	77.2 - 78.8	80 - 84
B	74.1 - 77.1	70 - 79
B-	72.6 - 74.0	65 - 69
C+	71.1 - 72.5	60 - 64
C	65.0 - 71.0	41 - 59
C-	62.7 - 64.9	35 - 40
D	51.7 - 62.6	15 - 34
F	0 - 51.6	0 - 14

Figure 2 Curved Grading Scale for the SUS (Lewis & Sauro, 2018)

The standard interpretation of the scale is that values between -0.8 and 0.8 represent a neutral evaluation of the corresponding scale, values > 0.8 represent a positive evaluation and values < -0.8 represent a negative evaluation. All the scales demonstrated positive evaluation (see Table 1 below). However, it should be noted that efficiency was marginal, and so further investigation is needed to achieve improvement in this area.

Table 1 Mean and standard deviations of 6 scales of the User Experience Questionnaire (UEQ)

UEQ Scales	Mean	Standard Deviation
Attractiveness	1.467	0.73
Perspicuity	1.520	0.85
Efficiency	0.810	0.58
Dependability	1.150	0.41
Stimulation	1.190	1.08
Novelty	1.600	0.58

Figure 3 below shows the comparison of results for the prototype with benchmark data. Novelty achieved the highest score (M=1.6, SD=0.58), and it was the only result located at the boundary of “excellent” and “good” descriptors. Attractiveness (M=1.467, SD=0.854), perspicuity (M=1.520, SD=0.922) and stimulation (M=1.190, SD=1.392) received positive feedback and achieved a “good” benchmark or above, which means that the prototype was evaluated more positively than 75% of the data set. Dependability (M=1.15, SD=0.640) had a benchmark score at the boundaries between “above average” and “below average”. Efficiency (M=0.810, SD=0.762) had the lowest score and was the only scale placed at “below average”.

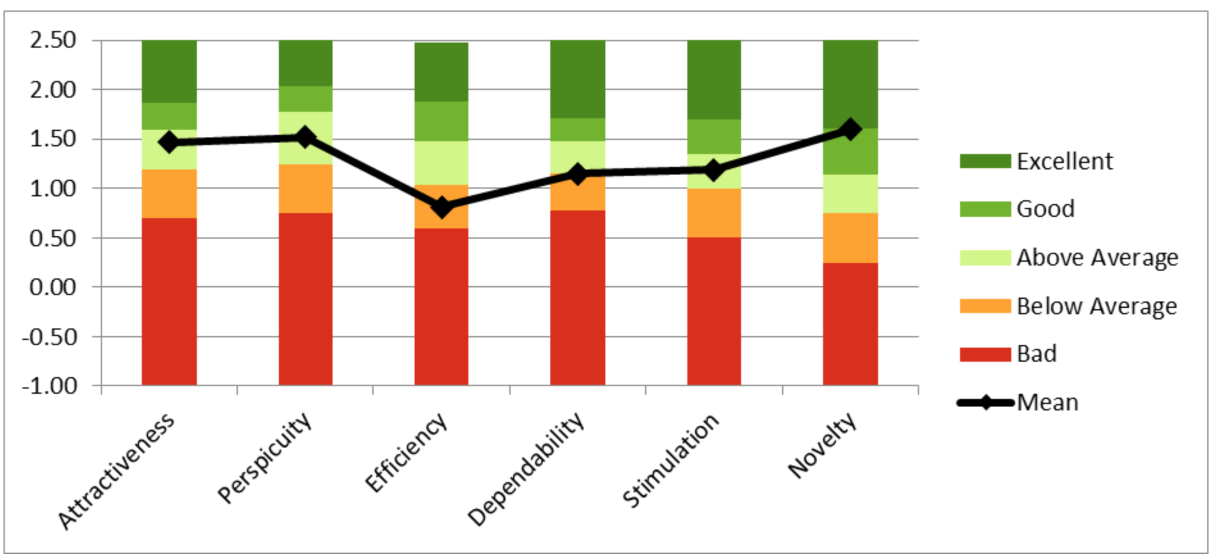

Figure 3 Comparison of results: prototype with benchmark data.

Table 2 Cronbach's Alpha-Coefficient of the 6 UEQ scales

UEQ Scales	**Average**
Attractiveness	0.69
Perspicuity	*0.41*
Efficiency	*0.32*
Dependability	*0.14*
Stimulation	*0.49*
Novelty	*0.47*

Discussion

According to the data obtained from UEQ, novelty obtained the highest score amongst the six scales (Table 2). This is unsurprising given that the textile utilizes mid-air gesture recognition, which is currently underexplored in research and not available on the commercial market. Consumers are not familiar with the concept and indeed this study was the first time that participants had interacted with this type of product.

Attractiveness, perspicuity, and stimulation all obtained "good" benchmark scores. Some of the e-textile products launched in the commercial market separate sensor and textile, with sensors linked to the textile externally. The gesture-controlled illuminative textile used in this paper integrates the sensors and the camera component and the POF fabric within the textile itself. The components are combined in a pleasingly non-intrusive manner and this probably accounts for the high score for attractiveness.

The colour-changing function of the textile can be controlled by a number gesture or any other pre-programmed hand gesture. These gestures are simple and intuitive, and so the user is able to control the e-textile easily. For these reasons, perspicuity achieved a "good" level of satisfaction.

The illuminating and colour-changing effects created by the illuminated POF have stimulating effect on the user. They also provide motivation for users to interact with the textile via gestures since most participants find the colour-changing effect enjoyable. Unsurprisingly, users awarded a "good" benchmark score for stimulation.

Efficiency attracted the lowest rating among all scales. Efficiency measures the prototype in regard to: slow/fast, inefficient/efficient, impractical/practical and cluttered/organized. There were several limitations in our product which could have led to the low score for efficiency to begin with the items low/fast and inefficient/efficient suffered from the unstable responsiveness of the color-changing effect due to sub-optimal WI-FI connection. Responses were sometimes immediate but just as frequently were significantly delayed.

Feedback obtained from participants reveals that they enjoyed using natural number gestures to trigger colour changes. Since natural numbers are universal and widely used in daily life, such gestures provide an easy and memorable way to interact with the product. Participants' feedback also lent support to the idea that customization would be popular. Most participants were keen on the idea of using unique personalized gestures. Personalization allows more freedom and encourages creativity but the problem of delayed responsiveness proved to be inhibiting. Participants would expect the colour of the product to change right after they performed a gesture, but instead they were met with delays of up to 3 seconds. The prolonged response time led to a degree of user confusion, which affected the perceived usability of the product. The prototype obtained a SUS score of 69.6, which indicates that there is room for improvement in the design of the prototype textile in particular the responsiveness.

Problematic data were detected in the low Alpha-Coefficient of the dependability scale. Problematic data patterns can be detected when the difference on the scale between the best and the worst evaluations is greater than 3. Problematic data could indicate random response errors or a misunderstanding of items. Two participants recorded problematic data on more than one scale, and both recorded problematic data on the dependability scale. This provides a possible explanation for the low Alpha-Coefficient of the dependability scale.

Suspicious data could result from participants misinterpreting items. The item unsecure/ secure, for example, can be interpreted in various ways, and multiple interpretations of an item are especially common when participants undergo a novel experience. This increases the difficulties of evaluating our prototype in the context of use. Another reason for the appearance of problematic data may be that some of the questionnaire items are poorly matched to the properties and functions of the prototype. UEQ is a comprehensive measurement of user experience. However, when a product is at the prototype stage and has novel features, some of UEQ questions might not be relevant at this stage in the development process. This means that participant responses may be inconsistent since they find it hard to evaluate the product if questions appear to be irrelevant .

Conclusion

This paper has summarized the usability evaluations of a gesture-controlled illuminative textile developed by the authors. The study was conducted with a randomly sampled group of 25 adults. The results of the learnability and UEQ and SUS tests have been reported and discussed. It is important to note here that the learnability score supports the claim that the prototype system is easy to use. However, the highest score among the six scales was achieved for novelty. Participants had not previously encountered an AI textile and clearly found it innovative and creative.

Attractiveness, perspicuity and stimulation all achieved 'good' benchmark scores. The gesture-controlled illuminative textile described here integrates the sensors including the camera component and the POF fabric within the textile itself, and so gives the sense of harmony which resulted in a high score for attractiveness. Perspicuity reached a satisfactory level as the textile can be controlled by a simple number gesture or any other preprogrammed hand gesture to trigger the colour-changing function easily. The textile also provides motivation for the user to interact with the textile via gestures to enjoy the colour changes, which led to a “good” benchmark score for stimulation.

In contrast, efficiency was rated below average. This is largely due to the unstable response time of the textile system. The current system is reliant on wi-fi stability and at times delays in colour changes occur, which have a negative effect on participant perceptions of efficiency. The usability test results have provided the authors with important insights on user perspectives.

After analysing the data from the usability test of the prototype gesture-controlled illuminative textile, there are 5 recommendations for future research. Firstly, to facilitate the development of user-friendly human-computer interaction, it is important to include the study of left-handed gesture recognition as the investigation of hand gestures in different positions, for an all-round gesture recognition system. Secondly to recruit a larger number of participants for future usability testing so to be able to gather additional user feedback for further development. Thirdly, to explore the feasibility of product mass customization by developing efficient system recognition of personalized hand gestures is suggested. Fourthly, to gather qualitative feedback via interviews with participants that helps elaborate and explain test results with comprehensive information. Finally, to further investigate alternative technologies to improve on the response stability. Overall, the positive results indicate that users found the prototype to be exciting, and viable for further exploration.

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