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Human Factors Evaluation of an Ambient Display for Real-Time Posture Feedback to Sedentary Workers

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ABSTRACT While multiple previous studies have proposed utilizing an ambient display for providing real-time posture feedback to seated computer workers, it is not well understood how effective ambient feedback is in supporting the users' dual task of computer work and posture monitoring/rectification. The objective of the current study was to evaluate an ambient display for real-time posture feedback in comparison with typical conditions, an on-screen display and no display condition, in terms of the dual task performance. The ambient and the on-screen display were also compared in terms of perceived detection efficiency and user acceptance measures. A total of 24 participants performed the dual task in each of the three display conditions (the ambient, on-screen and no display conditions). The dependent measures for the dual task performance were the number of typed answers and the occurrence rate of high-risk postures; and, for the subjective evaluation, two detection efficiency measures (visibility and understandability) and four user acceptance measures (performance expectancy, effort expectancy, attitude toward using technology and social influence) were employed. The study demonstrated that both the ambient and the on-screen displays enhanced the dual task performance with respect to the no-display condition and the ambient display was superior to the on-screen display in the subjective experience measures.

INDEX TERMS Ambient display, dual task performance, multiple resource theory, real-time posture feedback system, sitting posture.

I. INTRODUCTION

Many office workers perform their job tasks in poor sitting postures instead of the ones recommended in the ergonomics literature – this occurs even when the workers are provided with an ergonomic workstation [1], [2]. The poor postural behaviors seem habitual and difficult to change [3]. Working in high-risk postures for a prolonged duration is a threat to worker's health and it is known to be a risk factor for work-related musculoskeletal disorders [4]–[6].

In order to help seated workers correct their habitual postural behaviors, different intervention methods have been proposed. Several studies investigated the effects of providing relevant education/training and promoting self-monitoring and rectification [7]–[9]. The intervention based on self-monitoring, however, is limited in that the workers need to continuously maintain attention to their own postures while performing the primary work task – divided attention generally lowers one's ability to inhibit a habitual behavior [10]. In an attempt to address the limitation of self-monitoring, several studies have developed real-time posture feedback systems [11]–[33]. These systems monitored a seated worker's posture continuously over time and provided warnings to the worker when poor postural behaviors occurred. The systems have been implemented as wearable devices [12], [14], [25], [29], camera-based systems [18], [20]–[22], [24], and sensor-embedded chairs [15], [16], [19], [28], [30]–[33] or cushions/textiles [26], [27].

To office workers performing a primary work task, posture monitoring/rectification with the aid of a real-time posture feedback system becomes the secondary task. Hence,

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the feedback display for the system needs to be designed to provide the feedback in a less attention-grabbing way, so that it does not interrupt the primary task. One desirable design solution would be an ambient display that presents information by changing the surrounding environment in a subtle and unobtrusive way [34], [35]. Relatedly, Jansen [36] also proposed that a properly designed ambient interface could be an effective information delivery medium for the preoccupied users.

Indeed, some studies have explored and/or investigated ambient displays for notifying postural state or sedentary behavior to seated computer workers. Daian *et al.* [37] developed an ambient display with andromorphic design, which was located near the computer screen and provided postural feedback by movement and sound. Through observation and interview, the study found that the participants felt positive toward the display without being irritated. Haller *et al.* [16] comparatively evaluated a vibrotactile, a graphical, and a physical display. The vibrotactile display provided postural feedback using vibrations on the seat pan. The graphical display was an on-screen display in the form of an alert window. The physical display was a flower-shaped ambient display physically placed near the computer – it bent its stem to provide postural information and shook itself to motivate the user to take a one-minute exercise break. The participants were instructed to exercise each time the display provided the feedback. The results showed that in comparison with the other two display conditions, the physical (ambient) display was the least disruptive to the primary computer task. Hong *et al.* [38] also developed a flower-shaped ambient display, which provided high-risk posture alerts in a similar way to Haller *et al.* [16] and some extra information concerning the level of postural stress (e.g., sitting time and back curvature) by adding some design elements (e.g., sound and stem colors) – the display was not empirically evaluated. Wolfel [39] also developed a similar flower-shaped ambient display; one distinct design characteristic was that the flower mimicked the participant's postural behaviors by changing the angle of its stem. The study suggested that that ambient display is an acceptable display alternative for presenting postural information to computer workers.

Despite the previous studies mentioned above, however, the utility of using an ambient display for real-time postural feedback is currently not well understood. The previous studies are limited in that they did not evaluate posture feedback displays employing objective performance measures for the primary computer work and secondary posture monitoring/rectification tasks but rather rely on subjective measures. Evaluating the impacts of using an ambient postural feedback display on the dual task performance of computer workers would provide important information concerning the ergonomics design of effective sitting posture feedback systems.

Therefore, in an effort to contribute to the ergonomics design of real-time sitting posture feedback systems, this study had two objectives. The first objective was to comparatively evaluate an ambient display against two typical conditions (an on-screen display and a no display condition requiring self-monitoring without feedback) in terms of the dual task performance. An on-screen display was adopted as a typical display design alternative because it pertains to one of the most widely used and studied approaches for providing a real-time posture feedback [11], [12], [14], [18]–[20], [22], [24], [27], [33]. The second objective of the current study was to compare the ambient and on-screen displays in terms of perceived detection efficiency and user acceptance.

To achieve the two research objectives, the current study first developed two real-time posture feedback systems. Each of them consisted of a sensor-embedded smart chair and a posture feedback display. The two real-time posture feedback systems employed identical sensor-embedded smart chairs, which in real time classified the user's posture as one of multiple predetermined posture categories. On the other hand, they adopted different posture feedback displays: the ambient and the on-screen display. The ambient display was designed by the authors through the applications of the human factors display design principles [40], [41]. The on-screen display employed in this study was similar to those of the previous studies [11], [12], [14], [18]–[20], [22], [24], [27], [33]. Some distinguishing design characteristics between the two displays are specifically stated in the section II. B. Then, the three display conditions (no display, on-screen display, and ambient display) were evaluated in terms of the user performance during a dual task (a computer work task and the posture monitoring/rectification task); and lastly, the two displays were compared in terms of perceived detection efficiency (visibility and understandability) and user acceptance (performance expectancy, effort expectancy, attitude toward using technology and social influence).

II. DEVELOPMENT OF REAL-TIME POSTURE FEEDBACK SYSTEMS

A. SENSOR-EMBEDDED CHAIR AND POSTURE CLASSIFICATION MODEL

The current study developed two real-time posture feedback systems each of which consisted of a sensor-embedded smart chair, a posture classification model and a posture feedback display.

The sensor-embedded smart chair and the posture classification model were common to the two real-time posture feedback systems, and, were designed to classify a person's instantaneous posture as one of eleven ergonomically relevant posture categories (Fig. 1). They were: (1) keeping back against lumbar support, (2) erect sitting, (3) forward inclination, (4) left legs crossed, (5) right legs crossed, (6) leaning left, (7) leaning right, (8) lumbar convex, (9) slumped sitting, (10) left trunk rotation, and (11) right trunk rotation. Posture categories 1and 2 were grouped as low-risk postures and the rest of the posture categories were grouped as high-risk postures. The eleven posture categories were determined by analyzing existing ergonomics design guidelines [42]–[52].

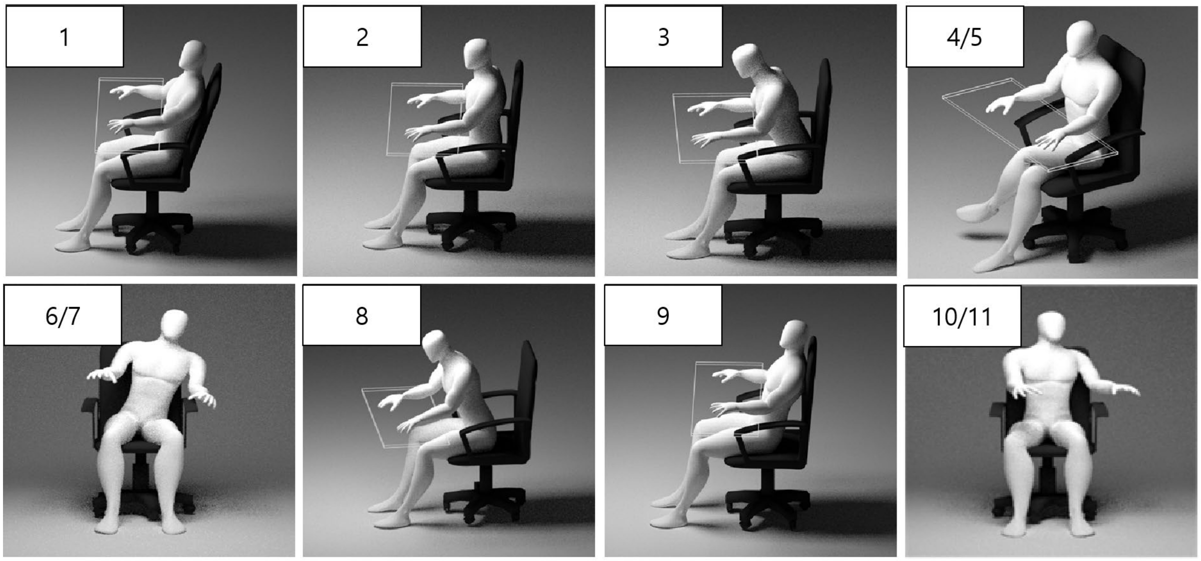

FIGURE 1. Eleven sitting posture categories: (1) leaning on the seatback while keeping the back straight, (2) detaching the back from the seatback and keeping the trunk erect, (3) flexing the trunk forward (slouch), (4) crossing the left leg, (5) crossing the right leg, (6) leaning against the left armrest with lateral bending, (7) leaning against the right armrest with lateral bending, (8) sitting on the edge of the seat pan with convex trunk, (9) leaning on the seatback with hips slightly forward (slump), (10) rotating the trunk to the left and keeping the trunk erect, and (11) rotating the trunk to the right and keeping the trunk erect.

The sensor-embedded smart chair was made by attaching a mixed sensor system to a general fabric office chair. The specific chair dimensions were: 46 cm in width and 53 cm in height for the seat back; and 48 cm in width and 44 cm in depth for the seat pan. The seat height and armrest positions were adjustable. The mixed sensor system consisted of: 1) six force resistors attached to the seat pan for measuring pressure distribution (green rectangles in Fig. 2); 2) six infrared reflective sensors embedded in the seat back for measuring distances between the upper-body and the seat back (yellow circles in Fig. 2); and 3) an Arduino microcontroller and a MATLAB (MathWorks Inc.) code used for processing/managing sensor data.

The common posture classification model was a neural network model. A total of 20 participants participated in the data collection for model development and validation. The participants posed each of the eleven predefined postures in the sensor-embedded smart chair. For each measurement trial, data from six force resistors and six infrared reflective sensors were collected at a sampling frequency of 10 Hz for 1 minute; the median value of each time series was determined and was transformed to the corresponding value in the SI unit of distance or pressure. A neural network model consisting of four hidden layers and 200 neurons was trained to classify a person's instantaneous sitting posture based on sensor measurements. The data collected from fourteen randomly selected individuals among the twenty participants were used as the training dataset and those from the remaining six participants were used as the test dataset for the cross validation. The cross validation results showed an overall accuracy of 90.2%.

B. DEVELOPMENT OF POSTURE FEEDBACK DISPLAYS

The two real-time posture feedback systems employed different types of posture feedback displays: an ambient and an on-screen display. Their function was to visually inform the user in real-time whether he/she was sitting in a low-risk posture (Posture Categories 1 or 2) or a high-risk posture (Posture Categories 3∼11).

Based on the past studies on taxonomy of ambient display [53]–[56] and the previously developed on-screen displays for posture feedback system [11], [12], [14], [18]–[20], [22], [24], [27], [33], the current study considered the following distinguishing design characteristics between ambient display and on-screen display in developing the two posture feedback displays:

- Ambient display provides information in an abstract or indirect way, while on-screen display does so in a direct or straightforward manner [53]–[55].
- Ambient display is located outside the primary task area, while on-screen display is placed in/near the primary task area [53], [54], [56].
- Ambient display allows effortless perception without requiring intentional glances, while on-screen display demands direct gaze for information acquisition [53], [54], [57].
- Ambient display presents information in a subtle way, while on-screen display does so in an attention-grabbing manner [53], [54], [58].

The ambient display was shaped like the moon and a cloud. The display was located on the right side of the computer screen (outside the primary task area), within 50 degrees of the eccentricity at the eye height, corresponding to the human

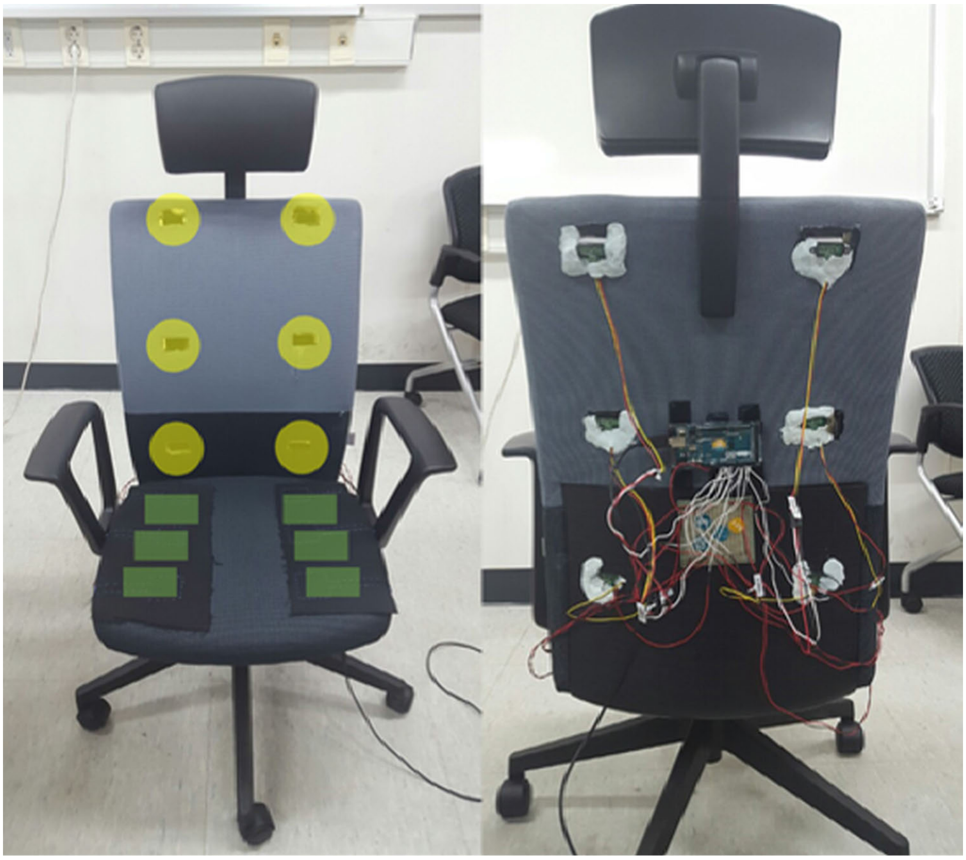

FIGURE 2. Sensor-embedded chair.

peripheral visual field [59]. To indicate the occurrence of a high-risk posture, the two objects, the moon and the cloud, were alternately illuminated every second (i.e., each object flashed with the frequency of 0.5 Hz) in red to create the first-order motion perception [60]; To indicate the occurrence of a low-risk posture, the moon and the cloud glowed dimly. These design decisions were made to utilize the peripheral vision as an extra visual channel in addition to the foveal vision, since the peripheral vision is sensitive to motion and luminance [40, Ch. 4, pp. 92], [41, Ch. 4, pp. 103].

On the other hand, the on-screen display was designed to look like a typical notification window offered by Microsoft Windows, a small window placed at the lower-right corner of the screen for providing app notifications. The design was based on the relevant GUI guidelines [61]. The display was near the primary task area, within 30 degrees of eccentricity where the human parafoveal vision would still allow color- and object-perception [62]. The display utilized an andromorphic icon (a relevant symbol) to represent the current postural state in a direct/straightforward way, by adopting an image of a person sitting upright for the low-risk postures, and a red image of a person sitting forward for the high-risk postures.

Fig. 3 shows specific design elements of the two posture feedback displays pertaining to their shapes, locations, and feedback designs.

III. EVALUATION OF POSTURE FEEDBACK DISPLAYS

A. PARTICIPANTS AND EXPERIMENTAL PROCEDURE

A total of 24 participants (14 males and 10 females) participated in this study and their mean age was 25.3 (standard deviation = 3.29, range: 20-31) years. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at Seoul National University. Informed consent was obtained from each participant.

Prior to the experiment, the participants were informed of low-risk postures and instructed to freely adjust the seat height of the sensor-embedded chair to their preferences. A training trial was provided to the participants so that they became familiar with the predefined high-risk postures, primary computer task, and secondary posture monitoring/rectification task. The computer work task consisted of mentally solving a series of basic arithmetic problems presented in Arabic number form and then typing the answers in verbal number form. The posture monitoring/rectification task required consciously avoiding high-risk postures and/or detecting and correcting a high-risk posture. Each participant performed a single experimental trial for each of the three display conditions considered in the current study (no display, on-screen display, and ambient display) – the experimental task was to perform the primary computer work task and

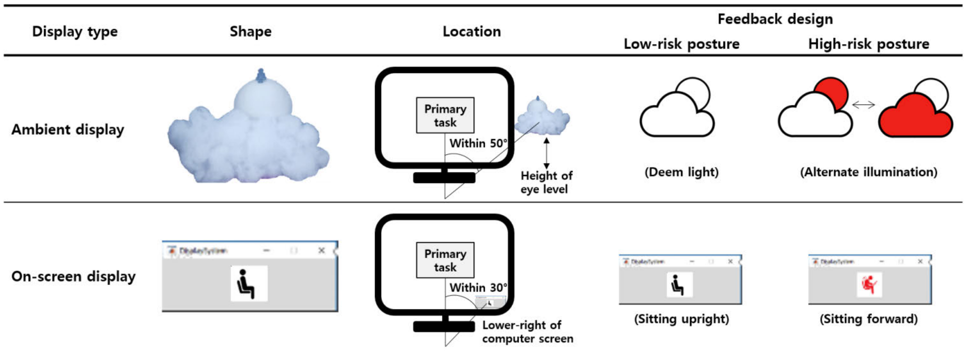

FIGURE 3. Posture feedback display (ambient display and on-screen display).

the secondary posture monitoring/rectification task simultaneously for 20 minutes. The order of the three display conditions was randomized for each participant. In the no display condition, the participants were not provided with any external postural feedback, and, thus, the condition served as the control for measuring the baseline dual task performance. As for the on-screen or the ambient display condition, the participants subjectively evaluated the feedback display in terms of detection efficiency and user acceptance at the completion of the corresponding experimental trial. The participants took a rest for 10 minutes or longer between consecutive experimental trials.

B. EXPERIMENT VARIABLES

The independent variable of this study was the display condition, which had three levels: no display, on-screen display, and ambient display. As for the dependent variables, two objective and two subjective measures were employed. The objective measures were number of typed answers and occurrence rate of high-risk postures. The subjective measures were detection efficiency and user acceptance. Each measure is described in detail below:

- Number of typed answers (count per trial): As mentioned above, the primary computer task in the current study was performing mental calculation and typing the answers. As a measure of the primary task performance, the number of the answers typed during each experimental trial was counted.
- Occurrence rate of high-risk (percentage of time): As a measure of posture monitoring/rectification task performance, the occurrence rate of high-risk postures is defined as the percentage of time the high-risk postures occurred throughout each experimental trial. As mentioned earlier, the real-time posture feedback system determined whether a high-risk posture occurred or not, with the frequency of 1 Hz, that is, 1 frame per second. Thus, the occurrence rate of high-risk postures was calculated as the percentage of the frames where high-risk postures were identified in each trial.
- Detection efficiency: Two subjective measures, visibility and understandability scores, were used to measure the efficiency in detecting posture feedback from each of the posture feedback displays. Visibility is defined as the degree of ease to which the participants could see the feedback display while conducting the computer task. The question given to the participants was ''How easy was it to see the posture feedback display during the computer task?'' Understandability is defined as the degree to which the participants could comprehend the feedback from the display while performing the computer task. The question given to the participants was ''How easy was it to understand the feedback from the posture feedback display?'' The participants responded to the two questions utilizing a 7-point semantic differential scale with the end points ''Very hard'' (1) and ''Very easy'' (7), and the midpoint ''Neutral'' (4).
- User acceptance: Four user acceptance measures, that is, performance expectancy, effort expectancy, attitude toward technology, and social influence, were employed to evaluate the extent to which the real-time posture feedback systems were appreciated/well-adopted by the user [39]. These four user acceptance measures were selected from the revised model of the unified theory of acceptance and use of technology (UTAUT) [63]. The description of measure and the question given to the participants for each measure are provided in Table 1. For each of the four measures, the participants answered the question using a 7-point Likert scale with the end points ''Strongly disagree'' (1) and ''Strongly agree'' (7), and the midpoint ''Neutral'' (4).

C. STATISTICAL ANALYSES

A one-way repeated measures ANOVA was conducted to test the effect of display condition (no display, on-screen display, and ambient display) on the dual task performance (number of typed answers and occurrence rate of high-risk postures). Mauchly's test was performed to assess sphericity of data for each ANOVA. In cases where the data violated the sphericity, degrees of freedom were corrected – the Greenhouse-Geisser correction was used when the Greenhouse-Geisser estimate of sphericity (ε) was less than 0.75; otherwise, the Huynh–Feldt correction was used [64], [65]. If the effect of display

TABLE 1. Four user acceptance measures.

Measure	Description	Question
Performance expectancy	A measure of an individual's belief in the system to help the secondary task of posture monitoring/rectification during the primary computer task.	"How much do you agree with the statement that adopting this posture feedback display will help you to correct the high-risk postures effectively during the computer task?"
Effort expectancy	A measure of an individual's effort required to use the system during the primary computer task.	"How much do you agree with the statement that it was effortless to use this posture feedback display during the computer task?"
Attitude toward using technology	A measure of an individual's attitude toward the way the system provides the feedback.	"How much do you agree with the statement that this posture feedback display provides the feedback in a nice and interesting way?"
Social influence	A measure of the degree to which an individual perceives the importance others imposed on the system.	"How much do you agree with the statement that people who are important/influential to you may think you should use this posture feedback display?"

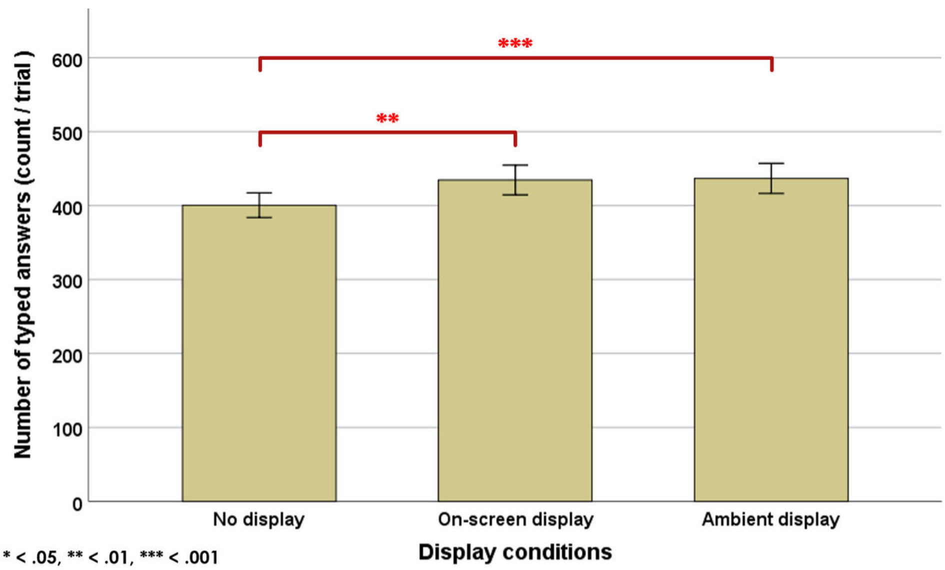

FIGURE 4. Multiple bar graphs for the number of typed answers with the results of the post hoc multiple comparisons.

condition was found to be statistically significant, post-hoc multiple comparisons with Bonferroni corrections were conducted.

In addition, a paired t-test was conducted to determine whether there was a statistically significant mean difference between the on-screen and the ambient display in each of the six subjective measure considered: two detection efficiency measures (visibility and understandability) and four user acceptance measures (performance expectancy, effort expectancy, attitude toward using technology and social influence).

All statistical analyses were conducted using SPSS 24 (IBM Corp.), and a p-value less than 0.05 was considered to indicate statistical significance.

IV. RESULTS

The ANOVA results showed that display condition significantly affected both of the two objective dual task performance measures, that is, the number of typed answers and the occurrence rate of high-risk postures, each with a p-value less than 0.001. For each of these two dependent variables, the mean of each display condition is shown in Fig. 4 and Fig. 5 with the results of the post hoc multiple comparisons. Note that in these figures, asterisks indicate significance in the pairwise comparisons, and error bars represent one standard errors.

As for the number of typed answers (Fig. 4), the no display condition ($M = 400.5$, $SD = 81.75$) had a smaller mean (i.e., less amount of computer task done) than the on-screen

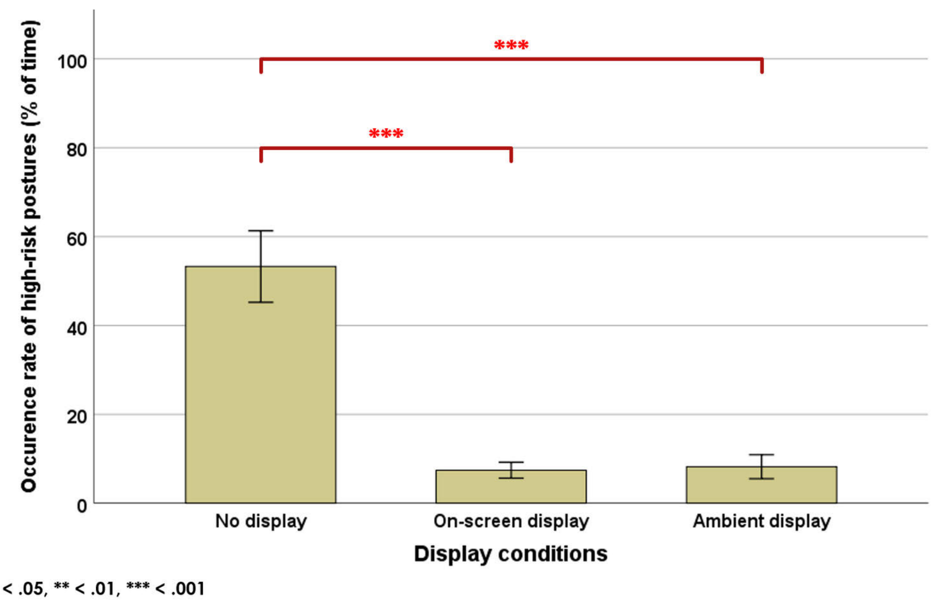

FIGURE 5. **Multiple bar graphs for the occurrence rate of high-risk postures with the results of post hoc multiple comparisons.**

display (M = 434.6, SD = 98.42) and the ambient display condition (M = 436.8, SD = 99.15). The on-screen and ambient display conditions were not significantly different from each other.

As for the occurrence rate of high-risk postures (Fig. 5), the no display condition (M = 53.27, SD = 38.58) had a larger mean (i.e., more occurrences of high-risk postures) than the on-screen display (M = 7.43, SD = 8.58) and the ambient display condition (M = 8.22, SD = 12.99). The on-screen and ambient display conditions did not significantly differ from each other.

The results of the paired t-tests for the detection efficiency measures indicated that the average visibility rating score was significantly larger for the ambient display condition (M = 5.44, SD = 1.55) than the on-screen display condition (M = 3.94, SD = 1.95); and that of understandability was significantly larger for the ambient display condition (M = 5.06, SD = 1.61) than the on-screen display condition (M = 3.31, SD = 2.02), each with a p-value less than 0.05.

Also, the paired t-test results for the user acceptance measures revealed statistically significant differences for performance expectancy and attitude toward using technology. The average rating score for performance expectancy was significantly larger for the ambient display condition (M = 5.02, SD = 1.12) than the on-screen display condition (M = 4.15, SD = 1.70); also, that for attitude toward using technology was significantly larger for the ambient display condition (M = 5.26, SD = 1.31) than the on-screen display condition (M = 4.28, SD = 1.76). Note that the two display conditions did not differ from each other in the average rating scores for the other two user acceptance measures (effort expectancy and social influence).

For each of these subjective measures, the mean of each display condition is shown in Fig. 6 and Fig. 7 with asterisks indicating the statistical significance in the t-tests and error bars representing one standard errors.

V. DISCUSSION

In an effort to contribute to the design of effective real-time sitting posture feedback systems for seated workers, this study examined the effectiveness of an ambient display for posture feedback in a human factors experiment. The research objective was two-fold: 1) to compare the ambient display against two typical conditions (an on-screen posture feedback display and a no display condition requiring self-monitoring without feedback) in terms of seated workers' performance of the dual task of computer work and posture monitoring/rectification, and, 2) to compare the ambient and on-screen displays in terms of perceived detection efficiency and user acceptance of seated workers.

Concerning the first research objective, the data analyses revealed that both the on-screen display and the ambient display developed in the current study provided significant advantages over the no display condition in terms of the dual task performance (Fig. 4 and Fig. 5). Compared with the no display condition, the on-screen and the ambient display showed 8.51% and 9.06% increases in the mean number of typed answers, respectively; also, the two displays showed 86.1% and 84.6% reductions in the mean occurrence rate of high-risk postures, respectively. These study results provide empirical evidence that well-designed posture feedback displays could significantly benefit the dual task of computer work and posture monitoring/rectification.

The substantial reductions in the mean occurrence rate of high-risk postures observed for the two posture feedback

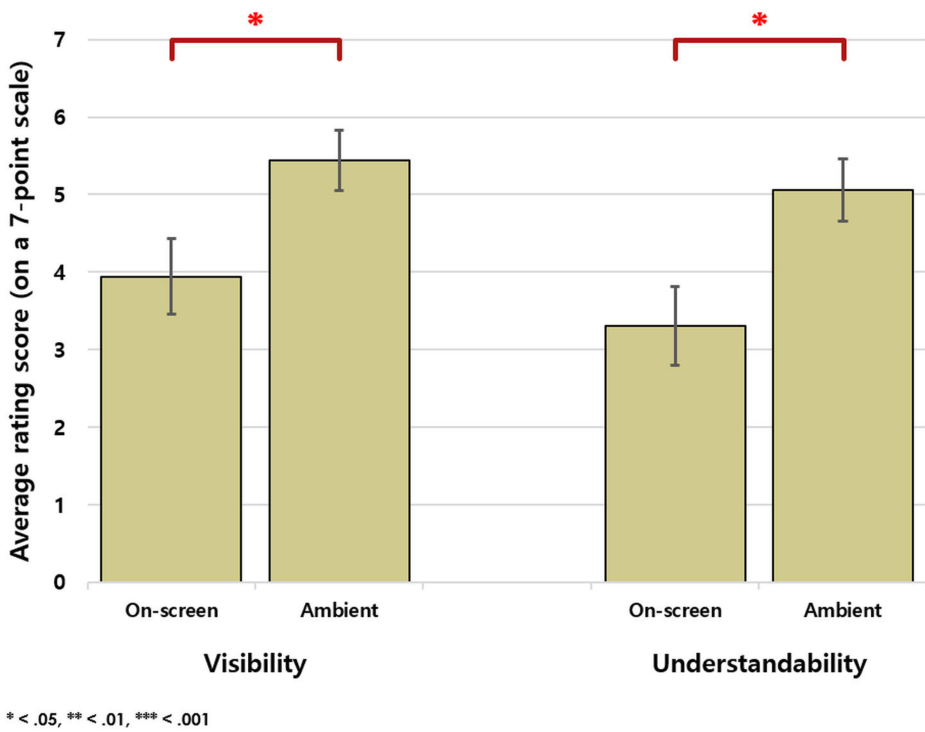

FIGURE 6. Multiple bar graphs for the average rating scores of the two detection efficiency measures with the t-test results.

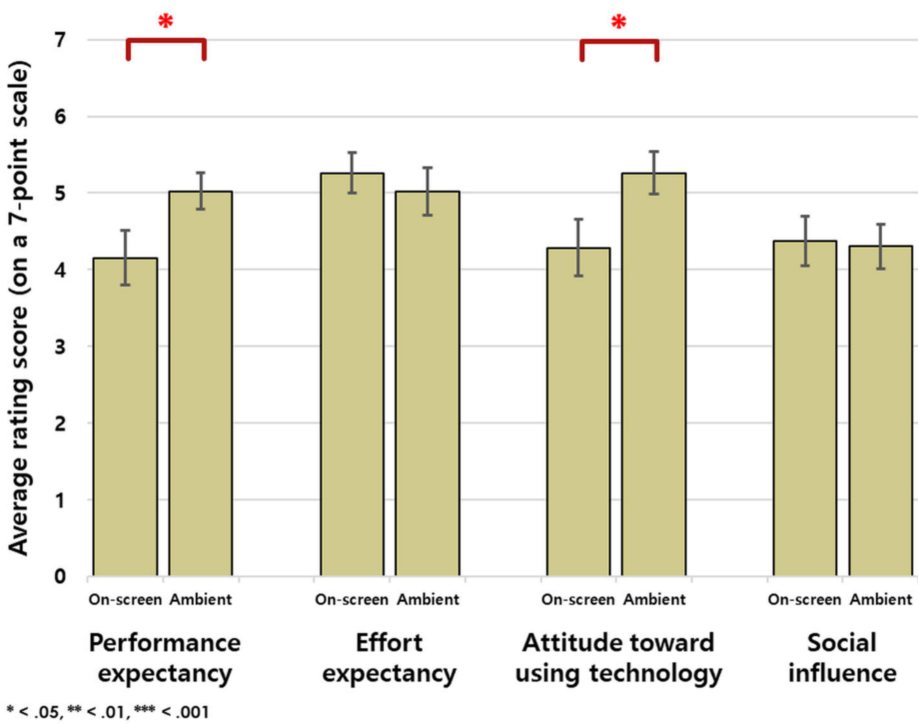

FIGURE 7. Multiple bar graphs for the average rating scores of the four user acceptance measures with the t-test results.

systems (Fig. 5) were expected as the systems were designed to directly support rapid detection of high-risk postures and prompt corrective actions. On the other hand, it is worth noting that the participants performed the computer work task better when they were provided with the posture feedback than when they were not (Fig. 4). This observation is somewhat counterintuitive at first glance since any additional visual feedback would naturally interfere with the visually intensive primary task. However, it may be explained in terms of the impacts of the posture feedback systems on the cognitive loads of the participants during the dual task. Each posture feedback system functioned as a surrogate cognitive system monitoring the user's sitting posture and providing the relevant feedback when necessary. It is thought that delegating the monitoring task to such a surrogate cognitive system likely resulted in a substantial reduction of the attentional resources required for the task, and, thus, allowed the participants to concentrate more on the primary computer task and improve its performance. Another possible explanation may be possible reductions in the physical task demands due to the posture feedback. Each posture feedback system decreased the occurrence of high-risk postures (Fig. 5) and thus likely reduced the physical task demands experienced by the participants during the dual task. Such reductions in physical demands could have contributed to the observed improvements in the computer work task performance. Multiple previous research studies have shown that during a multitask consisting of a physical and a mental task, reducing the physical workload can improve the performance of the mental task [66]–[72].

In regard to the second research objective, the ambient display was found to be significantly superior to the on-screen display for both of the detection efficiency measures (visibility and understandability). For both measures, the on-screen display had the average rating scores less than four (''Neutral''); on the other hand, the ambient display had the average rating scores greater than five. These results could be interpreted in terms of the anatomical characteristics of the human eyes - the distributions of the two photoreceptors, cones and rods, in the retina, and, relatedly, the differences between the central and the peripheral visual field in the perceptual characteristics. The cones enabling color perception are concentrated around the fovea, and, thus, as the eccentricity increases, color perception declines. On the other hand, the rods sensitive to motions and luminance changes are distributed mostly outside the fovea, and, thus, motion and luminance perception remains sensitive in the larger eccentricity [40, Ch. 4, pp. 92]. Therefore, while the primary computer task was being performed at the center of the screen in the foveal vision, the on-screen display only with slight changes in color and shape at the lower-right corner of the screen may not have been easily perceivable in near peripheral vision [62]; on the other hand, the ambient display placed right next to the screen may have been more perceivable by facilitating luminance and motion perception in the peripheral vision [60]. During the post-experiment interview, some participants made comments, such as ''the change in the surrounding environment (the ambient display) was more visible than the graphical change in the icon on the same screen where the computer task was performed,'' and ''while the ambient display allowed timely/natural perception without requiring much attention, the on-screen display did not catch the eyes, nor draw the attention.'' Such benefits of the ambient display agree well with the multiple resource theory that regards ambient vision as visual channel requiring almost no cognitive resource [73].

As for the four user acceptance measures (Fig. 7), both the ambient and on-screen displays had average rating scores greater than four ("Neutral") – such overall favorable/positive attitudes of the participants toward the two displays empirically imply the necessity/benefits of posture feedback systems for seated workers. In the measures of performance expectancy and attitude toward using technology, the ambient display (with the average rating scores greater than five) was significantly superior to the on-screen display. Relatedly, Wolfel [39] reported that the ambient display was favorably evaluated in terms of user acceptance measures.

The above results could be interpreted largely in association with the results for the detection efficiency measures (Fig. 6) mentioned earlier. It is thought that the participants considered the ambient display more helpful for fixing their high-risk postures than the on-screen display, due to its higher visibility and understandability. Also, the participants likely perceived the unique visual design of the ambient display more pleasing and interesting. It is encouraging that the greater detectability of the ambient display led to greater belief in its effects on posture correction and more positive attitude toward using the technology while improving the performance of the primary computer work task (Fig. 4). The consistent superiority of the ambient display across the subjective experience measures (detection efficiency and user acceptance) suggests that the participants developed a good overall impression of the ambient display. However, whether the positive halo effect occurred or not would need to be examined in future studies.

Despite the benefits of the ambient display, however, the post-experiment interview identified two design issues related to the current design of the ambient display. These design issues both pertain to divided attention and indeed conflict with each other. One design issue was concerned with the constant visual conspicuity of the ambient display. A couple of participants commented that the constant visual conspicuity of the ambient display with color-changing and blinking was disturbing during the computer work task. In fact, in addition to this issue of conspicuity-driven attentional capture, it is possible the mere presence of the ambient display itself required a certain degree of attention, distracting the participants with 'mere presence effect'. Relatedly, some studies revealed that the mere presence of mobile devices in the visual field diminished attention, leaving fewer cognitive resources available for other tasks, and degrading cognitive performance [74]–[76]. The other design issue was about "insufficient saliency of the ambient display." Some participants commented that the ambient feedback was not salient enough for them to recognize it immediately especially when they had little attention left, due to the perceptual workload from the primary computer task. Relatedly, Zheng and Morrell [19] also stated this attention tunneling issue in the context of vibrotactile postural feedback. To resolve this problem, the feedback would need to be provided in a more salient manner to prevent attention tunneling and accompanying inattentional blindness [77], [78]. Collectively, in improving the current design of the ambient display, the trade-offs between unobtrusive provision and timely detection of the feedback should be carefully balanced to enhance the dual task performance. One possible design solution may be to adaptively change the visual conspicuity of ambient feedback depending on the difficulties of the primary task or the individual's available attentional resources.

One notable observation from Fig. 5 and Fig. 7 was that although the occurrence rate of high-risk postures (i.e., the performance of posture monitoring/rectification task) did not show significant difference between the ambient and the on-screen display, the performance expectancy was significantly greater for the ambient display than the on-screen display. This hints at the possibility that the ambient display may perhaps lead to greater task performance of high-risk posture correction than the on-screen display in prolonged task conditions (i.e., longer than 20 min for each trial), or in more cognitively demanding task conditions. Admittedly, this idea is a conjecture and needs to be tested in future research efforts.

Overall, the current study showed that 1) well-designed posture feedback displays could significantly benefit seated workers during the dual task of computer work and posture monitoring/rectification; and, 2) between the two display design alternatives, the ambient display consistently surpassed the on-screen display across the detection efficiency measures (visibility and understandability) and user acceptance measures (performance expectancy and attitude toward using technology). Considering the dual task performance and the subjective experience in combination, the ambient display can be recommended as a desirable display design solution for posture feedback system.

Some practical implications of the current study results are provided here: first, considering the benefits of the ambient display demonstrated in this study, it is thought that in general, ambient displays could be useful for providing secondary task feedback in a variety of multitasking situations. Such situations may include screen-busy conditions (e.g., processing many/large/dynamic visual entities) where an on-screen feedback display occupying a certain screen area could make the screen busier, and thereby, cause or worsen visual clutter and information overload, and, also even screen-free conditions (e.g., reading a book or doing a manual work) where an on-screen feedback display cannot be implemented. With the inherent flexibility in the usage, ambient displays could be utilized to provide new/useful real-time feedback to a wide range of users, including the seated workers considered in the current study.

Also, the study results suggest the possibility that ambient displays could be extensively applied to the development of a variety of real-time feedback systems for breaking bad habits. Generally, breaking a habit requires prevention/reduction of habitual behaviors over a long period of time before a new habit is formed [79]. This process requires constant monitoring of one's own behavior, which can be a difficult task when having to perform a cognitively demanding primary work task. Such dual task and habit change could be effectively supported by a feedback system with an ambient display, with its significant advantages demonstrated in the current study. Indeed, multiple studies have shown that ambient feedback was successful in changing individuals' behaviors in applications such as increasing physical activity, improving lifestyle, and decreasing energy consumption, and affecting decision making [34], [58], [80]–[85].

The current study also adds a theoretical contribution to the current knowledge base regarding the multiple resource theory. This model, established by [86], has been widely applied to developing/(re)designing various multitasking environments for reducing cognitive workload and enhancing multitasking performance. The fourth dimension of the model is composed of the focal and ambient visions, and the ambient vision has been regarded as a residual channel for conveying additional visual information in an information-rich environment. For example, the ambient vision was proposed to be useful in informing the status changes of highly automated systems [87], and indeed, it was successfully adopted in the cockpit to present the status information, resulting in shorter mode transition time [88]. However, its application was limited to only providing the information relevant to the primary task. The authors are not aware of any previous display design studies that empirically utilized/validated the ambient vision as an information channel for the secondary task (completely irrelevant to the primary task) during multitasking. This knowledge gap regarding the fourth dimension of the model was partially addressed in the current empirical study as it demonstrated that the ambient postural feedback display was effective for conveying secondary task-related information while the focal vision was employed for the primary task. Of course, more future research is needed to strengthen the empirical base.

Finally, some limitations of the current study are acknowledged here along with future research ideas: first, given the ergonomic superiority of the ambient display against the two typical conditions (on-screen and no display conditions), further efforts may be warranted to comparatively evaluate the ambient display with other different types of posture feedback displays. Especially, its human factors evaluation in comparison with other displays developed for providing a real-time posture feedback with different single or mixed sensory (e.g., visual, auditory, and tactile) modalities [15], [16], [18], [19], [26], [29], [89] would help improve the current ambient display in the interface/interaction design. Second, as mentioned earlier, the long-term effects of the ambient posture feedback display on dual task performance, subjective experience, and, eventually, behavioral/habitual change need to be investigated in the future by conducting a longitudinal study (e.g., in actual office work environments). Third, although the sample size in the current study was adequate to allow statistical testing of the mean difference without concerns about low statistical power, further studies with more participants might be needed to obtain more accurate study results. Fourth, considering that age affects the performance of divided attention tasks [90]–[92], the beneficial effects of the ambient display on the dual task performance could be mediated by age [93], [94]. A follow-up study recruiting the participants with a broader range of ages will help understand the age effects on the benefits of the ambient display. Lastly, future human factors studies are needed to develop a real-time feedback system not only for the instantaneous high-risk postures that the current study focused on, but also for static postures as poor postural behaviors considering time factor – maintaining the same position for an extended period of time, even in a low-risk (neutral) posture, is another main risk factor for work-related musculoskeletal disorders [95].

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