Analysis of The Effects of Cognitive Stress on the Reliability of Participatory Sensing

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Abstract. As a result of the widespread of smart devices such as smartphones, participatory sensing, which is a method of sensing and sharing information about the surrounding environment using the user's own device, has been attracting increasing attention. However, the quality of the data relies on the attitudes of the users because they do not always give accurate and careful responses to participatory sensing tasks. In this study, we considered that the causes of the occurrence of careless responses in participatory sensing are not only the user's attitude toward the task, but also the cognitive stress conditions surrounding the user (e.g., time limits, ambient noise, walking). In this paper, we investigated whether the ratio of correct answers and the response status of a participatory sensing task differs under stressful and normal conditions. The results showed that the cognitive stresses of noise and walking significantly reduced the ratio of correct answers, whereas the cognitive stresses of walking and time limits increased and decreased the answering time, respectively. After the experiment, we conducted a subjective evaluation questionnaire regarding the effects of stress environment conditions on the participatory sensing task. The results showed that a combination of multiple stressful environmental conditions often hindered or affected task responses.

Keywords: Participatory sensing · Crowdsourcing · Response reliability · Satisficing · Cognitive stress

1 Introduction

Smart devices such as smartphones and wearable devices equipped with sensing, computing, and networking capabilities are rapidly growing in popularity. The widespread use of such devices has contributed to the realization of *participatory*

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sensing, a method of sensing and sharing information of surrounding environments using the user's own device [3]. Participatory sensing uses various sensors embedded in the devices of ordinary users, such as GPS, cameras, microphones, accelerometers, and gyroscopes. Therefore, it has the advantages of eliminating the need to install sensors and enabling data collection from a wide range of locations. However, the amount of data that can be obtained depends on the number of people who contribute to sensing tasks in the target area, and the quality of the data relies on the users' attitudes, since the user does not always give accurate and careful responses [1].

One of the risks to data quality in participatory sensing is careless responses, which is often explained in terms of *satisficing* (minimization of effort), where a person does not pay an appropriate cognitive cost for a given task [8]. The term *satisfice* is a composite of *satisfy* and *suffice*, and refers to a cognitive heuristic in which the finite nature of human cognitive resources leads to a tendency to minimize effort in response to demands, and to determine and pursue procedures that satisfy the minimum effort necessary to achieve an objective [22]. The attitude of users to a given task has been pointed out as one of the factors that cause satisficing [14]. Gogami *et al.* revealed the relationship between smartphone screen operation and satisficing, and as a result, built the careless response detection model [7].

In the real world, users typically use smartphones under various conditions that combine obstructive factors (e.g., noise, walking conditions) and mental factors (e.g., stress, mood). These factors affect smartphone operations, such as inducing a wrong operation [6,17,18,20].

From the above, we considered that the cause of a situation that a user gives a careless response is due to changes in not only the attitudes and behaviors of the user, but also obstructive factors surrounding the user (Fig. 1).

This study aimed to investigate the effects of obstructive factors on response reliability in a participatory sensing. In this paper, among the obstructive factors, we focused on "cognitive stress" and conducted an experiment to investigate its relationship with response reliability. In the experiment, we presented various cognitive stress conditions to participants while they were performing a specific participatory sensing task (questions about human flow). The correctness of the answer was used to assess the reliability of the users' responses. In addition, smartphone logs (embedded sensor data and touch panel operation) were used to analyze the effects of the cognitive stress condition in the users' responses. Based on these data, we analyzed whether the occurrence of careless responses or the smartphone logs differed under stressful and normal conditions. The results showed that the cognitive stresses of noise and walking significantly reduced the correct answer rate, and that the cognitive stresses of walking and time limits significantly reduced the answering time.

The organization of this paper is as follows. In Sect. 2, we outline existing studies related to the proposed method. Section 3 describes the analytical framework, Sect. 4 describes the setup of the survey experiment, Sect. 5 presents the experimental results and discussion, and Sect. 6 concludes the paper.

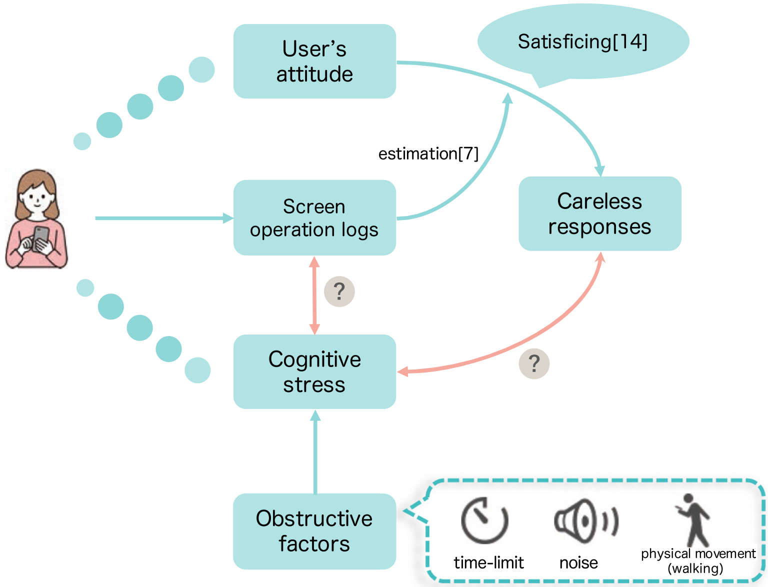

Fig. 1. Focus of this study

2 Related Work

Careless responses to questions in participatory sensing might introduce biases in the results of social surveys. Several studies have pointed out that there are many careless respondents, especially in online surveys [7,14,15]. Careless responses are thought to be caused by the attitude of trying to complete a questionnaire survey with the least amount of effort, which is referred to as *satisficing*, which several studies have attempted to detect. The details of these studies are described in Sect. 2.1.

In crowdsourcing, it has been shown that monetary incentives do not improve the quality of response data. We describe such a study in Sect. 2.2, which shows a method to inhibit careless responses to improve the quality of response data.

In addition, the influence of obstructive factors such as the stress surrounding the user on user behavior is also discussed in Sect. 2.3, as similar research has been conducted.

Based on these literature surveys, the position of this research is shown in Sect. 2.4.

2.1 Detection of Careless Responses

Several methods for detecting careless responses in questionnaire surveys have been proposed. Miura *et al.* [14] evaluated the efficiency and accuracy of the following methods for detecting careless responses: the Attentive Responding Scale (ARS) and the Directed Questions Scale (DQS) [10]. The ARS detects satisficing by scoring with two subscales: Inconsistency and Infrequency. Inconsistency is a measure of the difference in responses to questions that have similar meanings but different wordings. Infrequency is a measure of the difference in the choice that many people will select based on common sense and the choice actually selected. The DQS is a method in which some questions are inserted to instruct the user how to make a choice. If the user does not follow the instructions, he/she is considered to be satisficing. However, the predictive power of the various detection indices is generally not high; thus, it is more important to control the response environment or terminal depending on the survey content (e.g., instructing respondents to answer on a PC from home if the survey includes video stimuli). In addition, since these indices are similar to trick questions, they cause suspicion among the respondents, which increases their psychological burden and may result in careless responses.

Gogami *et al.* [7] developed a logger for smartphone screen operation and proposed a careless response detection method in online surveys based on features derived from obtained log data. As an example of these features, scrolling duration/speed/length, reverse scrolling, number of option changes, and text-deleting behavior have been newly employed. The results have revealed new features contributing to the improved accuracy of careless response detection in smartphone answer operation logs.

2.2 Suppression of Careless Responses

Crowdsourcing platforms such as Amazon Mechanical Turk have received increasing attention because of their ability to collect large amounts of data quickly and inexpensively [12]. Many studies have focused on how financial incentives in crowdsourcing affect the results of responses, and have shown that higher incentives for the same task increase the number of workers, but not the quality of the results [9,11,13]. On the other hand, volunteers have been shown not only to provide more reliable responses than crowdworkers who are given financial incentives, but also to have longer turnaround times and to be more likely not to complete the task. Therefore, volunteer crowdsourcing is inappropriate for time-limit tasks [2,5,16].

2.3 Effects of Stress on Behavior

In the fields of behavioral science and psychology, many studies have investigated the effects of stress on human daily life. Stress has been identified as a factor that is likely to have an impact on mobile interactions [19].

Sarsenbayeva *et al.* [18] used the Trier Social Stress Test to induce stress in participants and investigate the effects on performance in three common mobile interaction tasks: target acquisition, visual searches, and text entry. During stress induction, the access time and accuracy of the target in the target acquisition task and the completion time in the visual search task were significantly reduced compared with baseline.

Davide *et al.* [4] used a noninvasive approach to measure human stress levels by acquiring data from devices (e.g., touch operation, touch accuracy, touch intensity, touch duration, user movement, acceleration) and comparing the results during task execution in a stress-free environment versus a stress-affected environment (e.g., device vibration, loud and unpleasant sounds, unexpected device movement). The results showed that stress affected acceleration, the maximum and average touch intensity, user movement, and cognitive performance.

In addition, Schildbach *et al.* [21] focused on the background of the increasing number of people who use mobile phones while walking. They showed that walking, which can be an important environmental factor in mobile interactions, has a negative impact on tasks (e.g., target acquisition, text reading).

2.4 Study Position

Conventional research on careless responses has mainly focused on attitudes toward a given task, but has not considered the effects of cognitive stress from the outside world (i.e., obstructive factors). In participatory sensing, which is the subject of this study, we assume that the accuracy of responses is strongly influenced by not only human attitudes, but also obstructive factors. In this paper, we investigate the effects of obstructive factors on responses in participatory sensing by inducing cognitive stress in the user during the execution of a task.

3 Analytical Framework

3.1 Overview

To investigate the effects of obstructive factors on responses in participatory sensing, this experiment aimed to analyze how the quality of the responses and response behaviors change when users are subjected to the multiple cognitive stress conditions described below. The following participatory sensing scenarios were used. In this experiment, the user was asked to answer a question about people walking on the road, which could be confirmed visually while walking on the sidewalk. In the following sections, we describe the details of the analytical framework of the experiment.

3.2 Cognitive Stress Conditions

In this paper, we set up eight different cognitive stress conditions consisting of combinations of three different stress factors: answering under a time limit, answering in a noisy environment, and answering while walking. These stress environment conditions were set to simulate actual situations in participatory sensing, such as having a limited time to answer, being in a noisy environment such as a crowded urban area, and being in a situation in which a task is requested while moving. The details are shown below.

Cognitive Stress Due to Time Limits: In general, *time limits* are known to be stressful for the performance of any task. In the case of participatory sensing, time limits are considered to be severe because the user is required to observe and report within an ever-changing urban situation (e.g., information about people walking on the road in the scenario assumed in this paper) in a small amount of time, such as when waiting at a red light or at a meeting place. Therefore, time limit is included as the first stress factor.

Cognitive Stress Due to Environmental Noise: Environmental noise is perceived negatively by participants, with many commenting that it distracts them and negatively impacts their task performance [20]. In participatory sensing, it is assumed that the user is continuously exposed to the hustle and bustle of the city and other unpleasant noises while performing the task. Therefore, noise (in this case, urban noise) is included as the second stress factor.

Cognitive Stress Due to Body Movement (Walking): Walking negatively affects the performance of tasks (e.g., target acquisition, text reading) during interactions with mobile devices [21]. In the participatory sensing scenario assumed in this paper, the user is traveling on foot, and thus, is expected to move and perform the task at the same time. For this reason, we include walking as the third stress factor.

3.3 Investigation Metrics

As metrics that can be used in actual participatory sensing, we employ noninvasive data obtained from the device as follows.

Ratio of Correct Answers: In this experiment, we set a task in which the correct answer is uniquely determined; thus, the task answer rate is an index directly related to the reliability of the response. In this study, we hypothesized that the ratio of correct answers would change depending on the cognitive stress condition.

Answering Time: Stressed users rush through tasks, which results in lower task performance [18]. In this study, we hypothesized that the answering time would change depending on the given stress environment condition.

Table 1. Description of the devices used

Device	Main features
Smartphone (iPhone 11)	iOS 14.2 6.1-in. touchscreen (1792×828 px) Accelerometer (100 Hz)
Large monitor	42-in.
Speaker (BOSE Companion 20)	30 W

Acceleration (User's Movement): Using data obtained from an accelerometer built into the device, we analyzed how and how much the user moves during the task in participatory sensing, as well as the effects of stressful environmental conditions on the user's movements. A related study [4] reported that stressed users tend to move more or suddenly, so we hypothesized that the user's movement would change depending on the given stress environment condition (e.g., variations in acceleration and angular acceleration data).

Screen Operation: We obtained smartphone screen operation logs (e.g., single-tap event, double-tap event, location on the screen touched) during task answering. Then, based on these logs, we analyzed the influence of stressful environmental conditions on screen operation. We hypothesized that the operation in the application would differ depending on the given stress environment condition.

4 Experiment

4.1 Experimental Outline

Based on the defined analytical framework, an experiment was conducted with 20 high school and graduate students (age range: 15–24 years, gender: 19 males, 1 female). This study was approved by the Ethical Review Committee for Research Involving Human Subjects at the Nara Institute of Science and Technology (Approval No.: 2020-I-16). Written informed consent was obtained from all participants before the study began.

In-the-wild experiments posed the following problems for this study: (1) it is difficult to align the experimental conditions in outdoor environments (e.g., the difficulty level of the task cannot be controlled), and (2) some cognitive stress environment conditions cannot be controlled (e.g., noise cannot be removed). Therefore, we decided to conduct the experiment by constructing an indoor virtual environment. We used a windowless laboratory (21 m^2) in a university as the experimental environment. A large monitor was used to display crowd images in a city, and virtual urban background noise was broadcast through several speakers. The details of the equipment used in the experiment are shown in Table 1. The experimental environment is shown in Fig. 2. For the crowd images used in the experiment, 24 photos were selected from the CityStreet dataset [23]. Figure 3 shows an example photo.

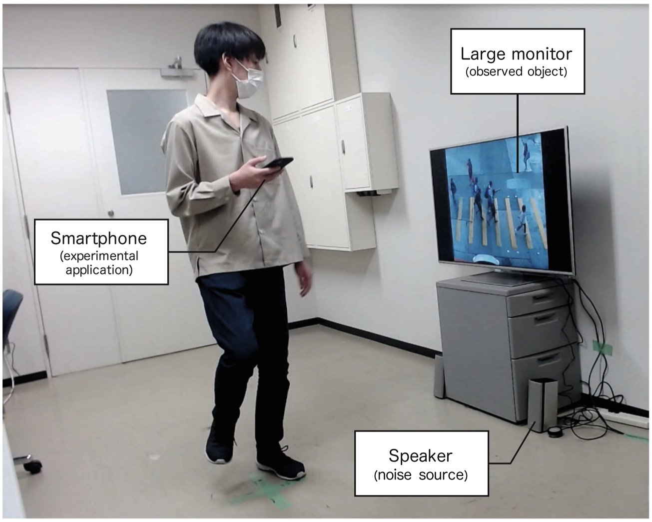

Fig. 2. Experimental environment

The specific task contents were set as follows according to the setting of the participatory sensing scenario in the analysis framework. These three questions are presented in a random order, and part of the question text (indicated by "⇔") is also presented randomly.

- How many people can you see in the photo?
- How many people are walking toward the "left" ⇔ "right"?
- How many people are walking "within" ⇔ "outside of" the crosswalk?

The cognitive stress conditions were presented as a set of $2^3 = 8$ patterns, as shown in Table 2. These are combinations of the presence and absence of three different stress items (i.e., time limit, noise, and walking) set in the analytical framework. The time limit was set at 10 s per question based on a preliminary survey of the time required to answer the above questions. We reproduced actual walking by marching in place in front of a large monitor so that it was always visible to the participants. To avoid order effects, these stress environment conditions were presented to the participants in random order.

4.2 Experimental Procedure

The experimental procedure is shown in Fig. 4 and below. The experiment, including the preceding explanations, took a total of about 30 min per participant.

Procedure 1) Preceding explanation to the participants
After entering the laboratory, the participants receive a briefing in advance. After explaining the outline and purpose of the study, the participants are

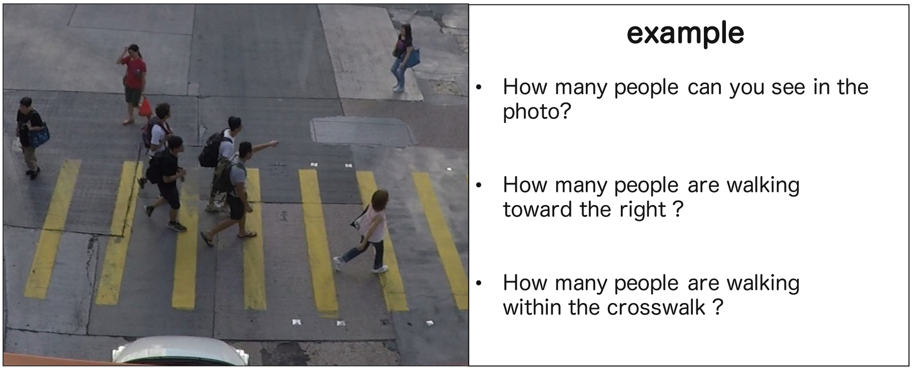

Fig. 3. Examples of crowd images used in the experiment and three questions [23]

Table 2. Obstructive factors

Pattern	Time limit	Noise	Walking
Pattern 0	✓	✓	✓
Pattern 1	✓	✓	–
Pattern 2	✓	–	✓
Pattern 3	✓	–	–
Pattern 4	–	✓	✓
Pattern 5	–	✓	–
Pattern 6	–	–	✓
Pattern 7	–	–	–

asked to fill out a consent form for participation in the study. Next, we explain the operation of the application to be used in the experiment (hereinafter referred to as the "experimental application"). Next, we explain the operation of the application used in the experiment (hereinafter referred to as the "experimental application") and ask the participants to try the task execution procedure once in the experimental application to become familiar with the operation. Finally, we explain the type of stress to be induced to the participants.

Procedure 2) Performing the task

The participant performs the participatory sensing task as instructed by the experimental application. The operation procedure in the experimental application is shown in Fig. 4 and below.

(A) Move to screen (B) by clicking the Pattern Display button. Resetting the order of the patterns and setting user IDs, which are for identifying each participant, are also done on this screen.

(B) The cognitive stress conditions for the trial are displayed. After confirming the cognitive stress conditions, the participant presses the Start button

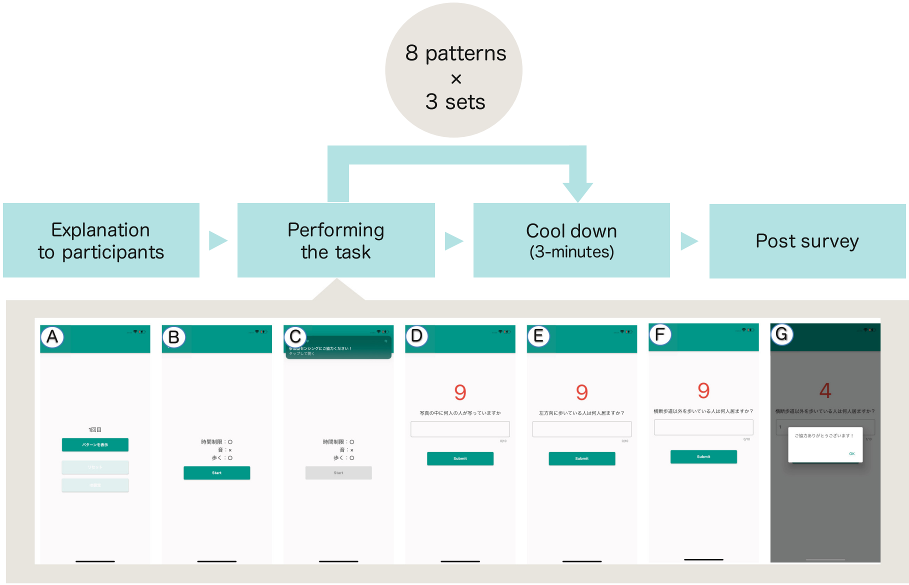

Fig. 4. Interface and operating procedure of the experimental application

to begin the experiment. Three seconds later, a notification from the experimental application is sent to the user's smartphone.

(C) Tap the notification message to go to screen (D).

(D–F) Task answer screen. When there is a time limit (time remaining), it is displayed as a red number. When the participant clicks the Submit button to submit his/her answer, the screen changes to the next. After answering the three tasks, the dialog shown in screen (G) is displayed.

(G) The Task Completion dialog box is displayed, and the experiment is completed. By clicking the OK button, the screen returns back to (A).

Procedure 3) Cool down

To prevent the effects of the previous stress conditions, a 3-minute rest period is provided after the completion of procedure 2).

Procedure 4) Repeat

Repeat procedures 2) and 3). In this experiment, three sets of eight patterns of cognitive stress conditions × were used, for a total of 24 trials.

Procedure 5) Post-survey

After all trials were completed, a post-survey was administered to the participants to provide a subjective assessment of the effects of the cognitive stress conditions on the participatory sensing task.

Table 3. Ratio of correct answers and answering time for each pattern

	Cognitive stress			Ratio of correct answers (%)		Answering time (s)	
	Time	Noise	Walking	Avg.	SD	Avg.	SD
Pattern 0	✓	✓	✓	0.667	0.149	17.767	2.575
Pattern 1	✓	✓	–	0.672	0.127	16.450	2.375
Pattern 2	✓	–	✓	0.656	0.101	17.150	2.443
Pattern 3	✓	–	–	0.711	0.122	16.400	2.205
Pattern 4	–	✓	✓	0.617	0.142	18.050	2.249
Pattern 5	–	✓	–	0.667	0.140	17.150	2.775
Pattern 6	–	–	✓	0.706	0.116	17.083	2.205
Pattern 7	–	–	–	0.706	0.136	17.417	2.189

5 Experimental Results

In this section, we present the results regarding the effects of stress on the participants during the participatory sensing task based on their responses and smartphone logs.

5.1 Analysis of Results

In this section, we present the results of the analysis of the evaluation indices. In this paper, only the results for the ratio of correct answers and answering time are discussed.

To examine the effects of the three types of stress items, a three-factor analysis of variance was conducted for each evaluation metric. To do so, we first averaged 480 data points (8 patterns $\times$ 20 people $\times$ 3 times) for each participant and obtained 160 data points (8 patterns $\times$ 20 people). A three-factor analysis of variance was then conducted based on the presence or absence of the three stress items (i.e., time limit, noise, walking). The mean values of the ratio of correct answers and answering time for each pattern are shown in Table 3.

The results of the analysis of variance confirmed that noise and walking stress showed a main effect (10% significance trend) on the ratio of correct answers. On the other hand, no interaction effect was found. These results indicate that the cognitive stresses of noise and walking cause differences in the ratio of correct answers. In other words, noise and walking stress degrade the ratio of correct answers.

Regarding answering time, we found main effects for walking (5% significance) and time limit (10% significance trend). In addition, we found an interaction (10% significance trend) of walking $\times$ noise. Therefore, we tested for a simple main effect of walking both with and without noise. We confirmed that, in the presence of noise stress, the presence of walking stress produces a significant difference (1% significance) in answering time.

These results indicate that walking and time-limit stresses lead to differences in answering time, i.e., walking and time-limit stresses lead to longer and shorter

Table 4. Post-experiment questionnaire results (Did these cognitive stress conditions hinder or affect your responses?)

	Cognitive stress			Choices				Average score
	Time	Noise	Walking	Never (1)	Not Very often (2)	Some of The time (3)	Most of The time (4)	
Pattern 0	✓	✓	✓	0 (0.0%)	1 (5.0%)	11 (55.0%)	8 (40.0%)	3.4
Pattern 1	✓	✓	–	1 (5.0%)	1 (5.0%)	15 (75.0%)	3 (15.0%)	3.0
Pattern 2	✓	–	✓	0 (0.0%)	4 (20.0%)	14 (70.0%)	2 (10.0%)	2.9
Pattern 3	✓	–	–	3 (15.0%)	8 (40.0%)	8 (40.0%)	1 (5.0%)	2.4
Pattern 4	–	✓	✓	3 (15.0%)	8 (40.0%)	8 (40.0%)	1 (5.0%)	2.4
Pattern 5	–	✓	–	9 (45.0%)	6 (30.0%)	5 (25.0%)	0 (0.0%)	1.8
Pattern 6	–	–	✓	6 (30.0%)	10 (50.0%)	3 (15.0%)	1 (5.0%)	2.0
Pattern 7	–	–	–	20 (100.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1.0

answering times, respectively. In addition, the results of a simple main effect test for walking × noise indicated that stress due to walking increases the answering time in the presence of stress due to noise.

We also analyzed the acceleration and screen operation logs in the same way, and found no correlations.

5.2 Analysis of Results of the Post-survey (Subjective Evaluation)

The results of the post-survey answered by the participants are shown in Table 4. The numbers below the column "Choices" indicate the number of respondents for each answer. In addition, the average of all respondents' answers is shown as "Average score" (1: no disturbance/effect – 4: great disturbance/effect). The higher the score, the more the cognitive stress conditions hindered or affected the responses.

As a result, we confirmed high scores of 3.4, 3.0, and 2.9 for Pattern 0 with all stresses, Pattern 1 with time-limit and noise stresses, and Pattern 2 with time-limit and walking stresses, respectively. In addition, we confirmed that the score decreased with the relaxation of the cognitive stress condition.

For each of the patterns 0 to 7, we asked the question *"Why did you think so?"*. Some of the collected answers are shown below.

- Pattern 0 (time limit, noise, walking)
  - The noise did not affect me much. Walking was a hindrance because of the increased eye movement. If the time limit were shorter, I might have been impatient.
  - I had to pay attention to the time limit, noise, and walking.
  - I felt a little distracted by the noise. It was a little difficult to count the number of people while walking because my vision was being shaken.
- Pattern 1 (time limit, noise, no walking)
  - I felt a sense of urgency because of the time limit and my concentration was hampered by the noise.
  - The time limit made me feel impatient. The noise was not a good feeling.
  - When counting a large number of people, the time limit made me panic. The noise did not bother me much.
- Pattern 2 (time limit, no noise, walking)
  - The eye movement takes a little time, so I thought it would have a slight effect.
  - When I counted a large number of people, I was in a hurry when there was a time limit. I was not bothered by the walking movements.
  - I feel impatient and the display was difficult to see.
- Pattern 3 (time limit, no noise, no walking)
  - Since there was no sound or walking, I was able to answer calmly despite the time limit.
  - There was relatively enough time to answer the questions, and it did not disturb my concentration.
  - I was not bothered when there were only a few people to count, but when there were many, I panicked.
- Pattern 4 (no time limit, noise, walking)
  - With noise and walking, I felt like I was using both my body and my brain.
  - Even if there were no time limit, I would not be able to tell how many people were counted in my head because of the noise. However, walking did not affect me much.
- Pattern 5 (no time limit, noise, no walking)
  - It was difficult to know how many people were counted when there was noise.
  - Because there was no time limit, I could count the number of people calmly. The noise did not bother me much.
- Pattern 6 (no time limit, no noise, walking)
  - I did not feel rushed because there were no restrictions other than moving.
  - Because there was no time limit, I could count the number of people calmly. I don't think the inclusion of walking movements had much of an impact.
- Pattern 7 (no time limit, no noise, no walking)
  - I was able to answer the questions carefully because there was nothing to interrupt me.

- Since there were no restrictions at all, I felt that it was most relaxing both mentally and physically.

As a whole, the respondents said that it was difficult for them to concentrate on answering when multiple cognitive stress conditions overlapped. When the number of people in the photo was small, the time limit did not bother them, but when the number of people in the photo was large, they felt rushed. As for the noise, the participants commented that it affected their answers because they felt it hindered their concentration. As for the cognitive stress caused by walking, the participants commented that it did not bother them as much as usual because it was an experimental environment and safety was taken into consideration. In future experiments, we would like to devise ways to present safe obstacles.

5.3 Discussion

The results of the present experiment and post-survey suggest that combinations of task types and obstructive factors cause different cognitive stresses. In this paper, we assumed that obstructive factors induce emotional effects such as impatience and restlessness. However, the results indicated that these factors also cause changes in task difficulty. For example, the task of crowd counting during walking requires paying more attention compared with a normal situation because the user needs to stabilize their gaze. The increase in cognitive costs for performing given tasks might result in careless responses. In future work, we will organize component elements of cognitive stress and investigate their relationships with obstructive factors.

6 Conclusion

This study aimed to investigate the effects of environmental factors on the response reliability of participatory sensing by inducing different cognitive stress conditions on the user during the execution of participatory sensing tasks.

In addition, we conducted a subjective evaluation of the effects of the cognitive stress conditions on the participatory sensing task after the experiment. The results revealed that the participants felt that combinations of multiple cognitive stress conditions hindered or affected their task responses.

The results of this experiment revealed that stress affects the ratio of correct answers and answering times, even in a safe indoor experimental environment, which suggests that users may feel more stress in actual participatory sensing. In the future, this hypothesis will be confirmed through experiments in scenarios similar to real environments.

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