Emergency Communication Protocols for Pleasure Boats Using Eye-Tracker and EEG

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Abstract. This study proposes a multimodal approach to assess the prototype of an innovative maritime communication protocol, based on a web-app, by monitoring cognitive load and physiological responses. The experimental design involves a simulation of an emergency navigation scenario, requiring communication with maritime authorities. Tests have been conducted in a laboratory environment with a group of non-professional pleasure boat captains who have obtained the boat license. Human factor analysis devices include an eye-tracker device to observe first glance and focus areas, an electroencephalogram headset to gather scores of cognitive loads focusing on interest and mental stress, and a Smartwatch for assessing vital parameters, such as heart rate and heart frequency, blood pressure, and oxygen saturation.

The study's primary goal is to assess cognitive load in terms of stress and attention and evaluate the simplicity of the platform's usage. This experimental approach allows us to recognize difficulties in web-based communication protocol usage. Furthermore, to reduce the likelihood of making a mistake during maritime emergency communications, this study proposes some user interaction improvements, potentially enhancing response efficacy and maritime safety.

Keywords: Human Factor · Maritime Communication · Safety · stress · cognitive workload

1 Introduction

Human factors are a crucial aspect of maritime safety. According to Allianz Global Corporate and Specialty [1], human error is pointed out as a contributing factor in 75% of maritime casualties. McCallum et al. conducted an in-depth analysis of maritime casualties discovering that 18% of accidents are caused by communication problems. For this reason, maritime emergencies demand rapid, accurate, and stress-resistant communication protocols. Information and Communication technologies (ICT) and communication protocols play a fundamental role in emergency management by reducing human error likelihood and improving boat captains' safety perception. Lack of training, knowledge, and proper preparation for recreational boat captains, can be considered as fundamental elements in leading boating emergencies [2].

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Fadda et al. [3] highlights the importance of human factor-oriented measures that are being applied in the maritime sector and can further contribute to giving maritime operators and recreational boat captains a focus for maritime safety interventions (such as tailored training programs or improved communication tools and protocols based on human factor research) which can potentially enhance maritime safety.

In the context of ISIDE (Innovazioni per la SIcurezza DEi mari) [4], a project funded by the European Union, has been developed an innovative maritime communication protocol to improve maritime communication's efficacy. This protocol is a prototype designed and proposed during the above-mentioned project and this study aims to assess, through a multimodal approach, the ISIDE's ability to reduce the likelihood of human errors. This multimodal approach takes into consideration the following dimensions:

- Communication efficiency: evaluate the efficiency of pre-set messages in an emergency scenario for a target group of recreational boat captains.
- Cognitive load: explore how stress affects the choice of messages and the effectiveness of communication for non-professionals.
- Application Usability: evaluate whether the ISIDE application's Graphic User Interface (GUI) is intuitive for a non-professional target group and facilitates rapid communication in critical moments.

The paper is structured as follows: Section 2 presents a literature review on human factors analysis in the maritime sector; Sect. 3 describes the material and methods; Sect. 4 describes the results and Sect. 5 concludes.

2 Literature Review

Several authors dedicate their research to maritime safety and accident prevention, recognizing human factors as a fundamental aspect of avoiding critical navigational situations. Using hierarchical clustering methods [5] analyzes historical data relating to maritime accidents to highlight the potential causal relationships that can describe homogeneous groups of accidents. The results point out the role of the human factor as the prevalent (or contributing) cause of marine accidents related to work operations. Chauvin et al. [6] present key concepts for Human factor analysis from psychology, to understand the Human factors' role in complex situations like maritime accidents. The paper by Hetherington et al. [7] identifies several human factors influencing safety such as fatigue, automation, situation awareness, communication, decision-making, teamwork, and health and stress.

ICT (Information and Communication technologies) innovations provide a lot of opportunities for the maritime sector. Despite the great innovation in navigation and communication systems, the need to develop harmonized standards arises. IMO (International Maritime Organization) in 2014 developed a strategic implementation plan for e-navigation to improve safety and reduce human error [8]. In the context of the e-navigation strategic implementation plan, IMO dedicates an important space to Human-centered design. Guidelines on usability testing, evaluation, and assessment of e-navigation systems are actually under development [9].

Tanoubi et al. [10] and Arslan et al. [11], uses eye-tracking technology respectively to explore testers' visual perception during simulation scenarios and to assess the usability of electronic information systems. They find insights into how individuals process visual information during an emergency. Interesting research by Ronca et al. validates an innovative safety framework HURID (Human Risk-Informed Design), experimenting on 26 maritime operators within a simulated critical scenario through EEG (Electroencephalogram) [12]. Also, Liu et al. [13] use EEG technology to study stress among crew members during communication tasks on a ship's bridge virtual simulator.

This paper, compared with the state of the art, proposes a validation of an innovative communication protocol by experimenting on a target group of non-professional recreational boat captains. Some author dedicates their study to recreational boating. McKnight [14] investigates the role of human error in recreational boating, instead, Virk and Pikora [15] develop a tool to measure safety in recreational boating. Finally, Kwang An [16] defines necessary e-navigation services for non-SOLAS (International Convention for the Safety at Sea), in particular fishing and recreational boats.

3 Materials and Methods

This section is divided into paragraphs to describe in depth the ISIDE protocol and the experimental scenario, the biometric and behavior analysis devices, and the data collection procedures.

3.1 Communication Protocol ISIDE

The actual protocol, based on voice communications through VHF (Very High Frequency) radio technology, often reveals limits of recreational boat captains, due to lack of training and stress, in sending correct communication during navigation, particularly in emergency situations. The challenging purpose of ISIDE is to reduce human errors during ship-to-ship and ship-to-land communication, particularly in critical moments. It brings a radical innovation in maritime communication by introducing technologies that allow maritime operators and recreational boat captains to send the correct information to their interlocutors.

The prototype of ISIDE protocol is based on a web application that allows, through an interface, the exchange of information to the nearest vessels and port authorities. Indeed, through the application, maritime operators and recreational boat captains can exchange free text messages and pre-set phrases following SMCP (Standard Marine Communication Phrases) [17], the standard phraseology proposed by the International Maritime Organization as well as sharing one's geographical coordinates.

3.2 Technological Devices and Software

Three technological devices and two related software were used to run the experiment and study stress and fatigue during the tests: a smartwatch a mobile EEG device with related software and a portable screen eye-tracker with related software.

The smartwatch is equipped with complex components for measuring vital parameters. Through specific commands, it is possible to obtain, at a specific moment, the tester's vital parameters such as maximum/systolic (SYS) and minimum/diastolic (DIA) blood pressure (measured in mmHg) with a margin of error of ± 3 mmHg.

The mobile EEG device, specifically the Emotiv EPOC X, is a technological helmet that uses 16 high-resolution electroencephalogram sensors to monitor during the test, the operator's cognitive parameters through their brain activity. It captures electrical signals from the brain and, through the algorithm available in the related software Emotive PRO, allows researchers to deduce cognitive states, such as engagement, excitement, stress, and relaxation, during specific tasks. The analysis can be performed in real time or by evaluating recorded sessions. The device maps 16 neural markers to assess mental commands, performance metrics, and emotional indicators with an impressive 88% accuracy rate. The primary data extracted from the EEG provides insight into the cognitive stress score (SS) and attention score (AS) of the trainee throughout the experiment, measured in a ten-second frame on a scale ranging from 1 to 100. Lastly, Tobii Pro Nano is a portable eye-tracker positioned at the bottom edge of a screen that can recognize the operator's eye gaze within a limited framework. Gathering eye-gaze position during a given fraction of time, eye-tracker returns, through the related software Tobii Pro Lab a map of the gaze concentration areas (Heat map) and a sequence of the eye-gaze points that allow to identification of first-glance areas (Scan path). The experiment was designed, managed, and run within the software Tobii Pro Lab.

3.3 Scenario

The scenario designed for the experiment reproduces a simulated maritime emergency. It describes, in a screen, a typical critical navigation situation in which a recreational boat captain could occur. Furthermore, the scenario screen described the scenario's details, and instructions to perform the task. The entire text of the narrative's scenario is reported as Appendix 1.

3.4 Questionnaire

An anonym questionnaire is developed to collect the tester's demographic information and a first impression about the communication protocol. It is divided into three sections, the first one collects general information about the tester, in particular: the tester's age, gender, nationality, and year of navigation experience. The second section is composed of eight questions with a ten-point scale response option. Questions can be divided into three dimensions:

1. Simplicity of use: three questions to understand whether, from the tester's point of view, the web app is intuitive and easy to use when exchanging messages.
2. Safety perception: three questions to discover the tester's safety perception during the task performance.
3. Usability during an emergency: two questions whether the tester considers the communication protocol useful, or not, during ordinary or emergencies.

The latter section, asks the tester to leave some feedback to improve the web-app or the protocol in general. A copy of the questionnaire is available as Appendix 2.

3.5 Experimental Design

The experiment process includes four main points. The first stage is dedicated to calibrating the devices (EEG and Eye-tracker) and the first vital parameters measurement for the tester. The tester was seated at an office desk with a PC in front of them. Eventually, the laboratory operator started to calibrate the devices before starting the test and the initial data collection of the tester's pre-stimulus biometric parameters. After all the tools were correctly set up, the experiment could proceed to the next phase.

The second phase is further divided into three fractions as follows:

- Scenario's administration: To begin, the first screen had a narrative about the described scenario and the instructions to complete the task.
- Pre-test stimulus: Introduction of the ISIDE application.
- Test performance: The web app works and the tester can go ahead and carry out the task assigned. The tester's goal is to send a distress signal, trying to follow the documentation written for the scenario. At the end of sending the distress signal, the screen was closed. This stage takes between 5 and 10 min, depending on the tester's choices.

The optimum task result that a tester can reach is to send a distress signal using only pre-set phrases. Anyway, the task is considered accomplished even if the tester uses free test messages.

The last phase starts with the second tester's vital parameters gathering. Finally, the tester is going to submit his opinion about the usage of the platform by completing a questionnaire right after completing the task.

3.6 Participants

The participants' selection was oriented on the ISIDE protocol target of recreational boat captains. For this reason, the participants were selected with the requirement of the boating license' possession. The sample involved during the experimentation was composed of 13 testers. Some general information about testers was acquired for basic demographical statistics.

The sample has an average age of 42, 40 years and, again on average, 18,70 years of experience in recreational navigation. Table 1 reports demographic information for each participant.

3.7 KPIs

To align experimental data with research purposes, a set of KPIs (Key performance indicators) was identified. It can be divided into three groups: tester task performance (measured by observing the tester), tester cognitive and vital parameters (measured with EEG and Smartwatch), and tester eye gaze movement (measured with eye-tracker). Table 1 reports the list of task performance KPIs, where the first column reports the KPI name, the following description, and the last one is the result or unit (Table 2).

Instead, Table 3 is structured as follows: the first column provides the KPI name, the second one shows the unit of measurement and the third column describes the formula.

Table 1. Participant demographic information.

Participant N°	Gender	Age	Nationality	Years of experience in navigation
1	Male	48	Italian	30
2	Female	29	Italian	15
3	Male	31	Italian	1
4	Male	32	Italian	2
5	Male	49	Italian	25
6	Male	58	Italian	38
7	Male	25	Italian	6
8	Male	36	Italian	14
9	Female	29	Italian	5
10	Male	50	Italian	19
11	Female	58	Italian	12
12	Male	45	Italian	25
13	Male	61	Italian	50

Table 2. KPIs for task performance.

KPI name	Description	Result/Unit
Task time	Overall time to complete the task	Min
Optimum performance	Task completed by using only pre-set messages	Yes/No

The last column specified the equation symbols. The quantitative human factor KPIs are composed using the scores provided by the mobile EEG device (stress and attention) and from the smartwatch (heart rate, maximum and minimum blood pressure).

For the vital parameters KPIs, a percentage change from the initial collection to the final collection was calculated:

$$\Delta\% \text{ change} = \frac{(X2 - X1)}{X1} \cdot 100$$

where:

For the cognitive scores:

X_1: KPI value measured in the Scenario's Administration

X_2: KPI value measured in the Test performance

For the vital parameters:

X_1: KPI value measured in the first collection

X_2: KPI value measured in the second collection

The analysis of the percentage change of the KPI values could help to better understand the variability of the measures recorded during the tests.

Table 3. Quantitative human factor KPIs.

KPI name	Unit	Formula	Equation symbols
Average stress score	[-]	$\mathbf{ASS} = \frac{1}{6}\frac{\sum \mathbf{SS}}{\mathbf{ST}}$	SS: Stress score ST: Task time [min]
Average attention score	[-]	$\mathbf{AAS} = \frac{1}{6}\frac{\sum \mathbf{AS}}{\mathbf{ST}}$	AS: Attention score ST: Task time [min]
Hearth rate	[bpm]	–	–
Max blood pressure/ systolic pressure (SYS)	[mmHg]	SYS	–
Min blood pressure/diatolic pressure (DIA)	[mmHg] DIA		–

Finally, the KPIs gathered from the eye-tracker. Specifically, the analysis of eye-gaze movement provides data about the first-glance movement after a specific stimulus (scan path) and the eye-gaze concentration area in a specific time frame (heat map).

4 Result and Discussion

4.1 Test Performance

Table 4 reports the test performance results for each participant.

The average time spent by the tester to accomplish the task is 3 min and 26 s and about 85% of the testers achieve the task using exclusively pre-set messages. Testers that spend more than the average time, coincide in parts with testers that accomplish the task using free-text messages.

4.2 Cognitive and Vital Parameters

The analysis conducted through EEG gives an overview of the cognitive aspects of subjects during the experimental phases. It was particularly interesting to monitor the cognitive parameters during the experimentation, excluding the calibration phase, and to divide the entire collection into three main phases: the scenario administration phase, the pre-test stimulus, and the task performance phase. The average scores collected and reported in Table 5 and in the bar plot in Fig. 1, revealed two main phenomena. The first displays cognitive attention scores without significant variations, but with a slight increase in the more critical phases, the scenario administration and the test performance. However, the cognitive stress scores highlight a continuous increase during the three selected phases, displaying an increase in stress even during the central phase of the stimulus administration. This phenomenon suggests an engagement of the subjects in

Table 4. Test performance KPIs.

Participant N°	Task time	Optimum performance
1	4′13”	Yes
2	3′16”	Yes
3	3′01”	Yes
4	3′28”	Yes
5	4′26”	No
6	3′14”	Yes
7	2′21”	Yes
8	2′23”	Yes
9	2′30”	Yes
10	4′25”	No
11	2′41”	Yes
12	4′09”	No
13	4′37	Yes

Table 5. Cognitive stress and attention scores and variations.

KPI name	Scenario’s administration	Pre-test stimuli	Test Performance	Variation %
Average cognitive stress	34,45	39,73	44	27%
Average cognitive attention	48,42	46,86	50,28	3,9%

the experimental scenario and a cognitive sensitivity due to not knowing and managing the unfolding events.

The vital parameter data, obtained as an average of the values from all participants in the experiment, provide a consistent view of the phenomenon from the perspective of the testers’ vital parameters. Table 6 reported the average values which can be observed a slight variation between the initial recording and the second recording at the end of the experiment. The slight increase highlights a physiological variation due to concentration during the tasks and a potential adaptation of the subject to the environmental factors of the laboratory.

4.3 Eye-Gaze Movement

Some of the most interesting aspects of this experiment are revealed by the eye-tracking analysis tool. Regarding this tool, given the dynamic nature of the application and the

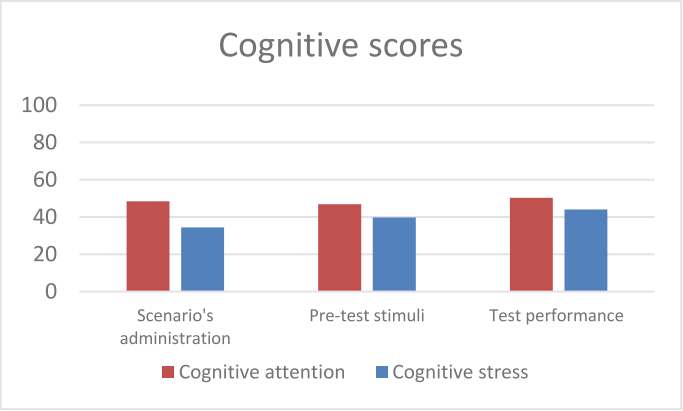

Fig. 1. Bar graph of the average cognitive scores (stress score and attention) divided for phase.

Table 6. Vital parameters scores and variations.

KPI name	First collection	Second collection	Variation
Average Hearth rate	71,92	76,46	7%
Average max blood pressure/ systolic pressure (SYS)	119	121,30	2%
Average min blood pressure/diatolic pressure (DIA)	77,92	82,23	6%

subsequent inability to have a holistic view of the phenomenon during experimentation, the focus has been on analyzing the most critical moments of the entire communication: the moment of sending the first distress call (MayDay) and the end of the conversation where feedback on the request for geographical coordinates and the arrival of rescue are received.

Initially, the inquiry was about the users' ability and speed in locating the GUI (Graphic User Interface) button to click to send the correct communication and, subsequently, the impact of other elements in terms of distraction from the focus of the moment. Figure 2 helps to track the first glance that the testers' gaze took during the presentation of the stimulus. In this figure is the reported gaze path for the whole sample. It is simple to recognize the different bubble colors. Each color represents a tester and the number inside the bubble is the sequence number recorded by the device. It emerged that the largest number of views and, consequently, attention focused on the correct button, the MayDay one.

Confirming the information gathered from the eye-tracking, Fig. 3 displays the eye-gaze heatmap. This figure, for readability reasons, reports the heatmap of one tester. The heatmap represents the intensity of viewing during the fraction of time in which the web app screen is shown for the first time. This insight makes it unequivocal that the

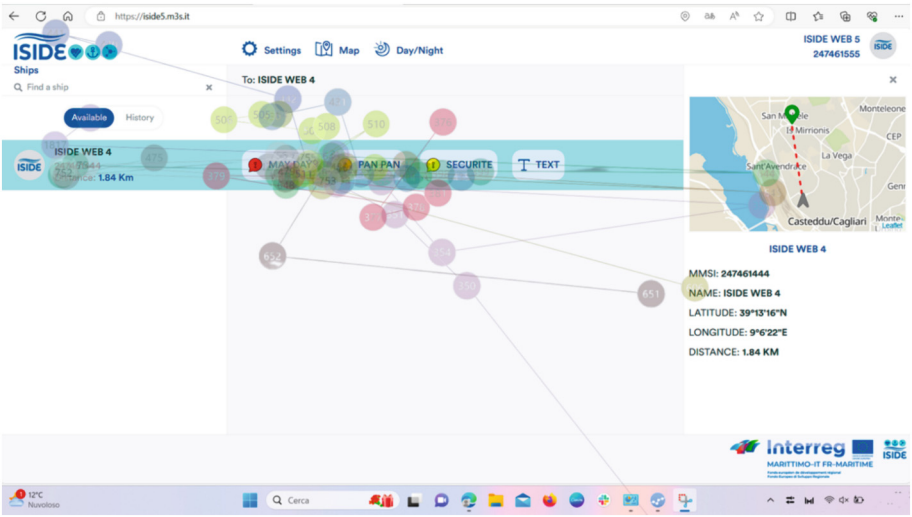

Fig. 2. Eye-gaze scan path recorded by the screen eye tracker.

subjects, despite some distractions to other areas of the screen, focused mainly on the correct point of the screen.

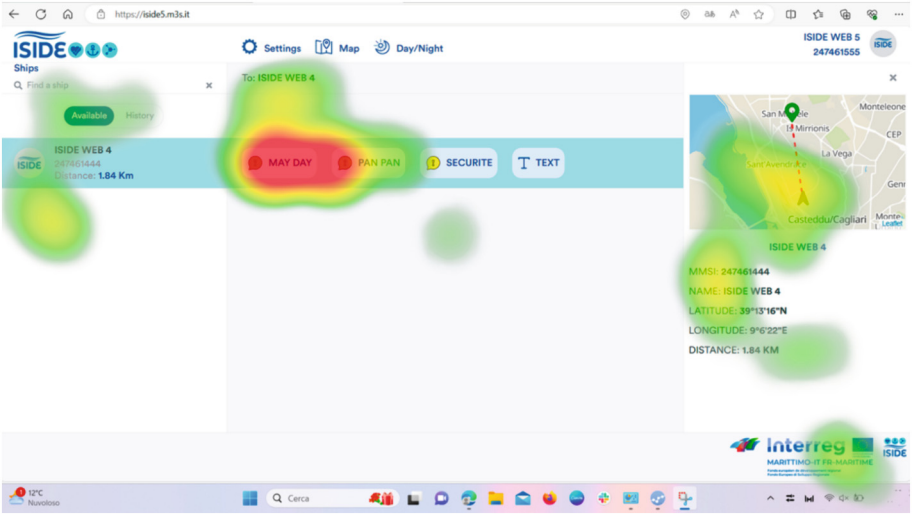

Fig. 3. Eye-gaze heatmap recorded by the screen eye tracker

4.4 Questionnaire

The questionnaire administered at the end of the experiment reports generally positive feedback. No tester offered suggestions for improving the application.

Despite all values being generally positive, the lowest score was observed in the section regarding the usability of the application during emergencies. Given the testers' proven navigation experience, this insight suggests a mistrust of using a technological/digital device during navigation. This phenomenon could arise from the actual lack of adoption of such systems as standard onboard communication equipment.

4.5 Limitations

Some limitations in this study are identified. The first important limitation of this study is the restricted sample size. The experiment was conducted on only 13 participants, consequently restricting the generalizability of the findings. Furthermore, the statistical power of the study is weak, which may lead to increased variance and potentially less reliable results. For this reason, this research could be considered a preliminary study for this experiment with the objective, for future research, to expand the size of the sample and allow more robust statistical analysis. On the other hand, is necessary to point out the real difficulties in gathering enough participants consistent with the target of the experiment.

Another important limitation could be identified in the simulated scenario. Even if the scenario could reproduce a real-life situation, it is not enough immersive to influence the human factor to predict with accuracy the behavioral variations caused by a real-life emergency. For further studies, could be interesting to replicate the experiment, always through a simulation, but in a real navigation situation at the sea taking into consideration the difficulties of catching target participants and the management of a real-life simulation experiment.

5 Conclusions

In conclusion, this experimentation, which focuses on a target group of pleasure boaters, suggests a further alignment of the application and, therefore, of the entire sea-to-land and sea-to-sea communication model proposed by the ISIDE project. This multimodal approach to user-focused experimentation validates the proposed communication protocol as suitable even for a less professionally trained public in navigation. The collected data suggest and confirm almost intuitive dynamics, in particular; the testers that use only the pre-set phrases spend less than the average time to send the distress message. The cognitive data provided by the EEG suggest that the uncertainty in the expectation of communication through an application has an impact on the subject's attention and stress levels, confirming the intuition to focus attention at that moment, and classifying it as more critical. The data provided by the eye-tracker entirely validate the simplicity and intuitiveness of the proposed model. The physiological parameters, acquired indicate an increasing concentration of the subject during the experiment and a physiological adaptation to the environment. The feedback provided by the testers at the end of the

experimentation validates the protocol but still hints at a slight mistrust regarding the use of innovative systems not yet familiar with the contexts of recreational navigation. On the other side, the restricted number of participants might not represent the population and, as a consequence, limit the ability to detect reliable variations that could be more apparent in a larger group. Future research with expanded sample sizes is recommended to validate and extend these preliminary findings.

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Appendix 1

Scenario

Welcome to the maritime emergency simulation experiment.

Today, you will find yourself at the heart of a critical situation at sea. Imagine you are the captain of the boat ISIDE5, sailing on the calm sea of the Mediterranean. The weather is clear, a gentle breeze accompanies the waves, and everything seems to be going well.

But in the meantime, something unexpected happens: your boat's engine went on fire. You find yourself in trouble, far from land, with a crew of 3 people relying on you. It's time to activate the emergency protocol.

Your first action is to use the ISIDE application to send a standardized distress message, following procedures, to the nearby ship ISIDE4. The series of messages you send must report crucial information: type of emergency, nature of the emergency, condition of the crew, and the request for immediate assistance.

No particular danger situations like explosions or injuries on board are detected.

But it doesn't end here. If necessary, you are allowed to use the free messaging feature to provide additional details.

Remember, your role is crucial: your actions and decisions can influence the outcome of this simulation. Ready to start? Face this challenge with calm and concentration. Your reactions and decisions will give us valuable information on how to improve maritime communication in emergencies.

Appendix 2

Questionnaire

General demographic information

- Years of experience in navigation: _____
- Gender: _____
- Age: _____
- Nationality: _____

Express your evaluation of the following aspects of the Application by marking the appropriate judgement (1 = Poor, 10 = Excellent):

Intuitiveness within the screens	1	2	3	4	5	6	7	8	9	10
Simplicity of use	1	2	3	4	5	6	7	8	9	10
Simplicity in sending communications	1	2	3	4	5	6	7	8	9	10
Perceived safeness during screens‘ surfing	1	2	3	4	5	6	7	8	9	10
Perceived safeness in sending communications	1	2	3	4	5	6	7	8	9	10
Perceived safeness in receiving communications	1	2	3	4	5	6	7	8	9	10
Usability in emergency situations	1	2	3	4	5	6	7	8	9	10
Usability in ordinary situations	1	2	3	4	5	6	7	8	9	10

Suggestions
Do you have any suggestions to improve the protocol?

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