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The effects of three environmental factors on problem-solving abilities during evacuation

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ABSTRACT

To escape a dangerous building emergency occupants may need to respond quickly, assess the environment, plan their actions and tackle possible problems during evacuation. In this study 147 participants were tested in an experimental evacuation design for the effects of three environmental factors (fire alarm, lighting and emergency exit signs illumination) on problem-solving abilities. The experimental evacuation scenarios consisted of: (1) fire alarm, normal lighting conditions and illuminated emergency exit signs, (2) fire alarm, dark environment and illuminated emergency exit signs and (3) fire alarm, dark environment and *not* illuminated emergency exit signs. The tested problem-solving abilities were the time to plan actions and number of excess moves on the Tower of London test. The main results indicate that the third experimental evacuation scenario led to a decrease of 25.9% in planning time, compared to the control scenario. Age also had a significant effect on planning time. The oldest participants took or needed on average 42 s more planning time than the youngest participants, an increase of 146.9%. Furthermore, the second and third experimental evacuation scenario led to significant more excess moves, compared to the control scenario. However, the older the participants the less excess moves they had. For gender no significant effects on problem-solving abilities were found. In addition, the relationships between problem-solving abilities and building evacuation time were investigated. Longer planning times were associated with longer evacuation times and more excess moves were associated with shorter evacuation times. Practical implications for building and safety managers are to add training in darkness or assume more evacuation time in darkness or for older aged populations in evacuation plans and drills. Future research should collect more quantitative data about effects of various environmental factors and personal characteristics, such as problem-solving styles, age and gender, on building evacuation behaviour.

1. Introduction

To escape a dangerous building emergency occupants may need to respond quickly, assess the environment, plan their actions and tackle possible problems during evacuation. According to earlier research, problem-solving is a crucial cognitive function in survival

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situations [1–3]. For instance, during an emergency evacuation occupants may be confronted with complex situations in the environment, such as wayfinding in smoke-filled or not illuminated corridors or dealing with obstacles on an escape route. These situations might require problem-solving for a safe and timely escape. Previous research indicates that smoke-filled or not illuminated environments or obstacles on an escape route can delay evacuation times significantly [4–7]. However, it is unclear how much time building occupants need or take to plan their actions and solve problems in emergency evacuations. In this study the effects of three environmental factors (fire alarm, lighting and emergency exit signs illumination) on problem-solving abilities during evacuation are investigated as well as the relationship between problem-solving abilities and building evacuation time.

Problem-solving consists of "goal-directed activity, moving from some initial configuration or state through a series of intermediate steps until finally the overall goal has been reached: an adequate or correct solution" [8]. Situations requiring problem-solving call for people to take some precautions (i.e. 'planning') in order to meet their goals (i.e. 'problem-solving') [9]. What occupants decide to do in a building evacuation depends on several factors such as the complexity of the environment, the changing dynamics of the situation or time pressure [10]. In any event, general planning seems fundamental for wayfinding in novel environments [11]. A building emergency is usually unexpected and novel, and occupants need to plan their actions and solve possible problems as quickly as possible. This is also the paradox here. During a real sudden onset building emergency, occupants are usually pressed for time, but to be able to find a way out, they must take a moment to assess the situation and environment, plan their actions and solve potential problems. In other words, planning and problem-solving take time, but time is usually limited in real emergencies. When in this paper the term 'problem-solving' is mentioned, this also includes 'planning'.

No studies could be found on how problem-solving abilities might be affected by environmental factors in emergency building evacuations specifically. However, there are studies that investigated the effects of other stressful psychological conditions on problem-solving task performance that might resemble stressful emergency evacuation conditions. This earlier research suggests that increasingly stressful psychological conditions have a negative effect on the performance of problem-solving tasks [12,13]. Porter and Leach [14] investigated Royal Air Force crew members who participated in a realistic simulation of an 'aircraft down' survival incident. In this study, the crew members were tested on their cognitive functioning in the field for four consecutive days after their aircraft supposedly crashed. They found significant impairments in the planning abilities and actions of the experimental group compared to the control group. The experimental group consistently took longer to plan their actions than the control group. Kamphuis et al. [15] investigated the effects of a physical threat on team processes during a complex task performance in a climate chamber. The physical threat consisted of letting the participants believe that in the climate chamber, the oxygen level would be reduced during performance of the problem-solving task (in reality this did not occur). The teams had to develop a plan to evacuate a group of people from a hostile area. The researchers found that the physical threat negatively affected the performance of the team on this problem-solving task. The evacuation plans of the teams under physical threat contained more than twice as many errors as of teams in the non-threatening condition. Cassidy [1] simulated an aircraft disaster exercise and investigated if the problem-solving styles of individuals would be related to their effectiveness in escaping from the simulated crash. He found significant correlations between speed of egress and problem-solving style. The results suggest that participants who exited the aircraft faster, scored higher on a more positive problem-solving style. Also, participants who had a significantly higher problem-solving style score were more likely to 'survive' the simulation [1]. This indicates that there might be a relationship between problem-solving abilities and evacuation time. However, specific studies on how problem-solving abilities might be affected by environmental factors in emergency building evacuations and what the relationship is between problem-solving abilities and building evacuation time are missing. Therefore, these topics are addressed in our study. Additionally, previous studies into problem-solving abilities show inconsistent results on possible age and gender effects [16]. For this reason, the effects of age and gender on problem-solving abilities are also investigated in this paper.

The first topic of our study is to investigate the effects of three environmental factors (fire alarm, lighting and emergency exit signs illumination) on problem-solving abilities in an experimental evacuation design. In the experimental set-up, three building evacuation scenarios were simulated and compared with a control evacuation scenario. In the control scenario there was no activated fire alarm, the lighting conditions were normal and the emergency exit signs were illuminated. The three experimental evacuation conditions consisted of: (1) a fire alarm, normal lighting conditions and illuminated emergency exit signs, (2) a fire alarm combined with a dark environment and illuminated emergency exit signs and (3) a fire alarm combined with a dark environment and *not* illuminated emergency exit signs. These conditions were chosen because in real (fire) emergencies these variables might also be present and/or absent. For example, in building emergencies usually a fire alarm is activated to alert occupants that there is an incident in the building. Also, it might be possible that due to a power outage rooms and/or corridors can become relatively dark. Although emergency exit signs are designed to stay activated in case of power outage, these signs can be out of order because batteries are not replaced in time or the signs are compromised or destroyed in building incidents. The second topic of our study is to investigate the relationships between problem-solving abilities and building evacuation time. The main research questions for this paper are:

1. What are the effects of three environmental factors on problem-solving abilities during evacuation?
2. What are the relationships between problem-solving abilities and building evacuation time?

Additionally, regarding the first research question also the effects of age and gender are investigated.

2. Methods

2.1. Participants

In total, 160 individuals participated in the experiments, from which 13 were excluded in the analyses due to computer problems with the administration of the problem-solving test, not following the instructions given by the researchers or not correctly set evacuation conditions in the room where the experiments were conducted. Hence, the results discussed in this paper are based on 147 participants: 72 men ($M = 51.92$ years, $SD = 16.59$) and 75 women ($M = 47.43$ years, $SD = 15.11$). The participants were recruited via (1) news items and advertisements in local newspapers in Arnhem and Velp (the Netherlands), (2) the distribution of flyers in several residential areas in Velp and (3) messages on Facebook sites of several local colleges, universities, sporting clubs and scouting clubs. For their participation, the participants received a financial reward of € 20. This study was approved by the Human Research Ethics Committee of Delft University of Technology.

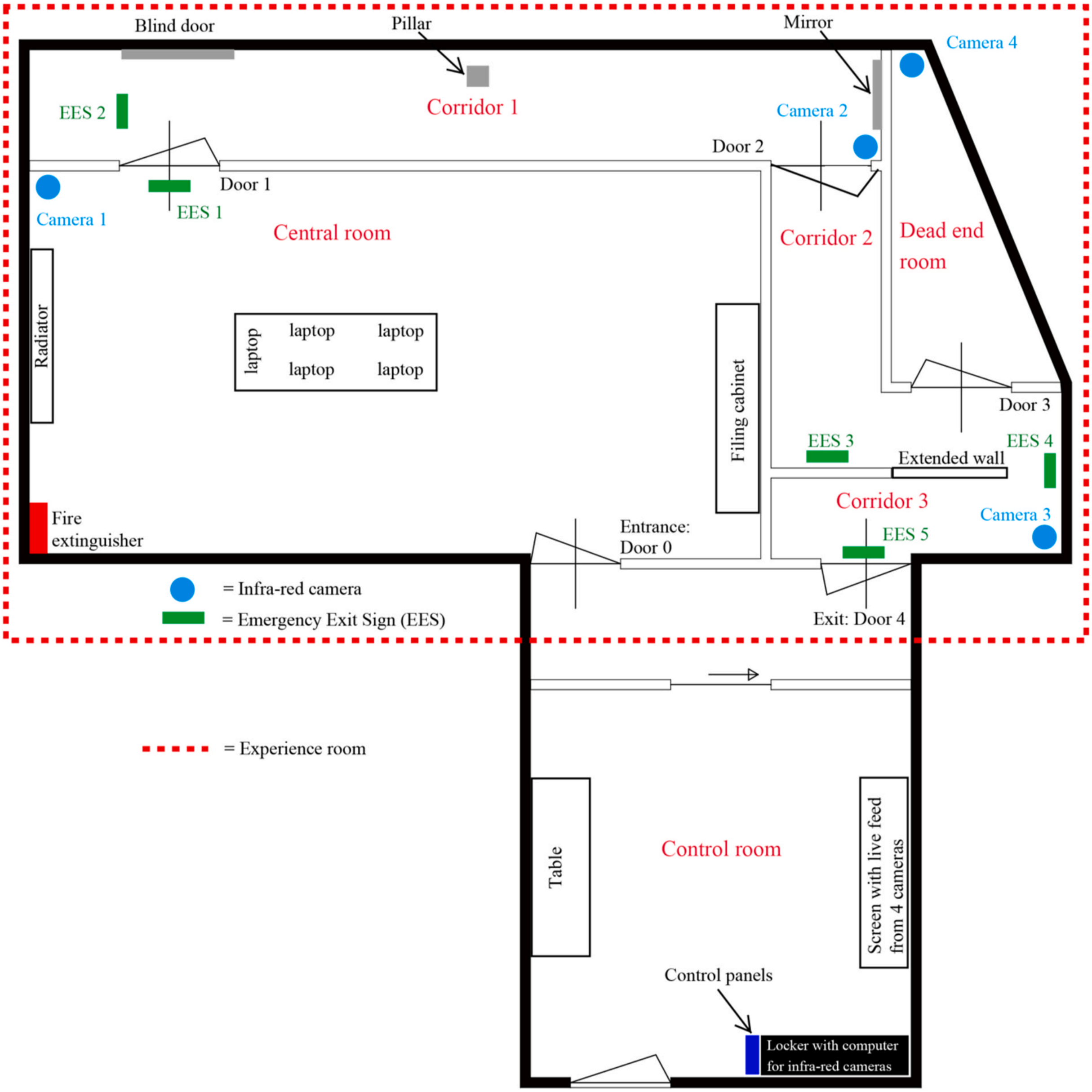

Fig. 1. Floor plan of the experience room and adjoining control room.

2.2. Experiment facility: experience room and adjoining control room

The experiments were conducted in the Netherlands in a facility, called the experience room, of a company specialized in emergency lighting. This company made this room available for our study, but they had no interference with our experiments. The experience room contained five green emergency exit signs, four infra-red video cameras (including a recording installation) and a sound installation system which included the sound of a fire alarm. These instruments could be managed on corresponding control panels, which were installed in the adjoining control room. See Fig. 1 for the floor plan of the experience room and the control room.

The experience room had four separated compartments. The first compartment, called the 'central room', contained a table with five laptops. On these laptops the Tower of London test (see section 2.4.1) was installed. On the right side, there was a filing cabinet and on the left side there was a fire extinguisher and radiator (cover). The second compartment, 'corridor 1', was a small corridor with, at the left side, a so-called 'blind door' (i.e. this door could not be opened). At the end of this corridor there was a mirror on the wall. There was also a pillar in the middle of this corridor. The third compartment had two corridors ('corridor 2' and 'corridor 3') which were partly separated by a wall. The fourth compartment was an empty room, with only one entry/exit (door 3). This room is called the 'dead end room'. Corridor 3 eventually led to the exit of the experience room, i.e. door 4.

The control room was equipped with two control panels on which the fire alarm, different lighting levels and the emergency exit signs could be (de)activated. With four infra-red cameras the activities of the participants in the experience room were monitored and recorded (see Fig. 1 for the exact locations). These recordings were used to measure the evacuation time of the participants.

The participants visited the building for the first time and therefore they had no prior knowledge of the layout of the building, nor any prior evacuation experience in this building.

2.3. Experiment design

The effects of the three environmental factors were studied in three different experimental evacuation scenarios and compared with a control scenario. In the experimental evacuation scenarios the following environmental factors were increasingly added to the control scenario: the sound of a fire alarm, darkness and not illuminated emergency exit signs (see Fig. 2).

In the control scenario, the conditions in the experience room were normal: there was no fire alarm activated, lighting conditions were normal and the five emergency exit signs were illuminated. In the first experimental scenario, the 'fire alarm scenario', the fire alarm was activated, lighting conditions were normal, and the five emergency exit signs were illuminated. In the second experimental scenario, the 'darkness scenario', the fire alarm was activated, lighting conditions were set at a very low level (<0.01 lux) but it was not completely dark because of the light of the illuminated emergency exit signs. In the third experimental scenario, the 'exit signs off scenario', the fire alarm was activated, the lighting conditions were set at a very low level (<0.01 lux), but now the five emergency exit signs were deactivated. The experience room was very dark and the emergency exit signs were not noticeable anymore. Appendix A contains photos of the lighting conditions in the experience room in the four evacuation scenarios.

There were 28 participants in the control scenario, 38 participants in the fire alarm scenario, 41 participants in the darkness scenario and 40 participants in the exit signs off scenario.

In total, there were 38 experimental runs in which one to five individuals participated at the same time and the different groups with participants were randomly assigned to a scenario. The intention was to have groups of 4 or 5 persons in each experimental run

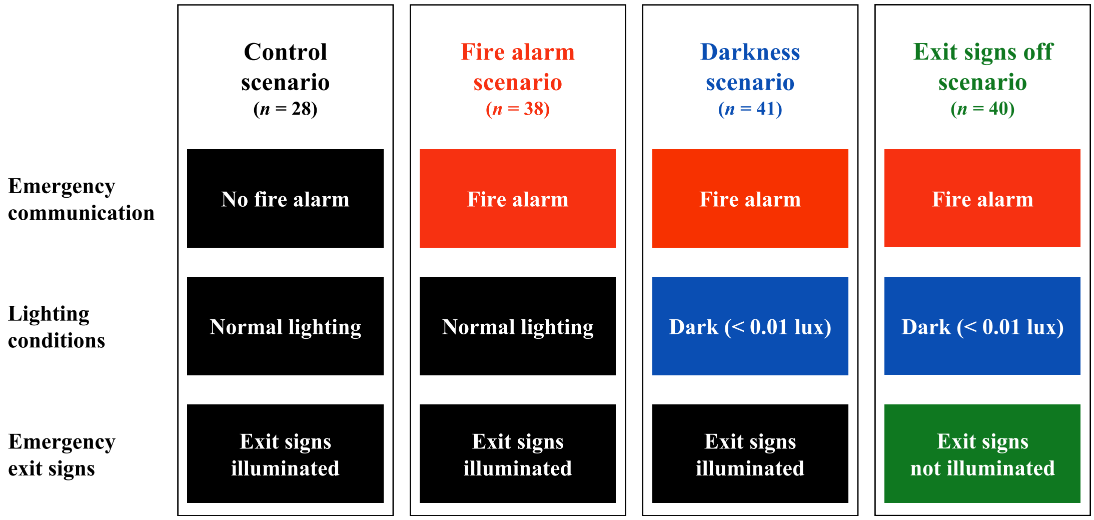

Fig. 2. Set-up of the four evacuation scenarios.

Table 1
Distribution of number of groups – per group size – in the four evacuation scenarios.

Group size	Evacuation scenario				Total
	Control	Fire alarm	Darkness	Exit signs off	
Group of 1	1	0	0	0	1
Group of 2	0	0	0	1	1
Group of 3	2	0	2	0	4
Group of 4	3	4	3	5	15
Group of 5	2	5	5	5	17
Total	8	9	10	11	38

and equal runs for all scenarios. However, due to no shows on the day of the experiment this was not possible. Table 1 shows the distribution of the number of groups per group size and per scenario.

2.4. Materials

This study was part of a larger research study in which also the effects of the three environmental factors on *building evacuation time* was investigated. The results of that study are presented in Kinkel et al. [17]. For the complete set-up, please be referred to this paper. An overview of the administered tests and surveys in the current study can be found in Fig. 3.

2.4.1. Tower of London test: problem-solving abilities

To measure problem-solving abilities, the Tower of London test was chosen. The Tower of London test has been widely used to assess executive functions, such as (spatial) planning and problem-solving, and it appears to be a suitable method to quantitatively analyse planning and problem-solving abilities [18]. Although this test does not literally represent a task building occupants are likely to perform during an evacuation, this test allows exact measurements of problem-solving abilities with detailed time and movement recordings in data files that can be analysed. Also, this test was chosen because Porter and Leach [14] used this test to measure cognitive functioning in an intensive military survival experiment after a supposedly 'aircraft down' incident. They found significant impairments in the planning and action components of the Tower of London test in the experimental group compared to the control group. The time it takes to perform this test can be considered as a pre-travel phase of an evacuation. The Tower of London test requires 'forward thinking' (i.e. planning), because an early incorrect move could make the problem practically unsolvable [9]. For this study, a computer version of the Tower of London test was used which was obtained from the test battery of the Psychology Experiment Building Language (PEBL), Version 0.14 [19]. The standard English instructions of the test were translated and programmed into Dutch. At the top of the computer screen the target example was displayed (see Fig. 4 for a screenshot of the test). The goal of the participants was to move the five discs, shown at the bottom of the screen, from their original configuration to the same position as illustrated in the target example at the top of the screen. Only one disc at a time could be moved.

The participants had to perform eight of these trials, but they were unaware of this exact number. The participants were only informed that they had to perform several trials of the test until a final score and the instruction to immediately evacuate the room was presented on the computer screen. The trials were programmed with an increasing level of difficulty, i.e. the trials differed in terms of number of moves required for solution. See Table 2 for the minimum required moves to solve the subsequent trials. To let the participants feel a sense of urgency, a timer of 30 s for each trial was added to the test (see Fig. 4).

The data of the Tower of London test was automatically collected and stored in.txt- and.csv-files on the laptops. In this paper the following scores are analysed: the *total planning time* (i.e. the time between seeing the discs on the computer screen and making the first move for all eight trials together) and the *total number of excess moves* (i.e. how many moves more than the minimum moves were necessary to complete all eight trials). Both measurements represent forward thinking (i.e. planning), and this is usually required in emergency situations to plan for a safe escape [20,21].

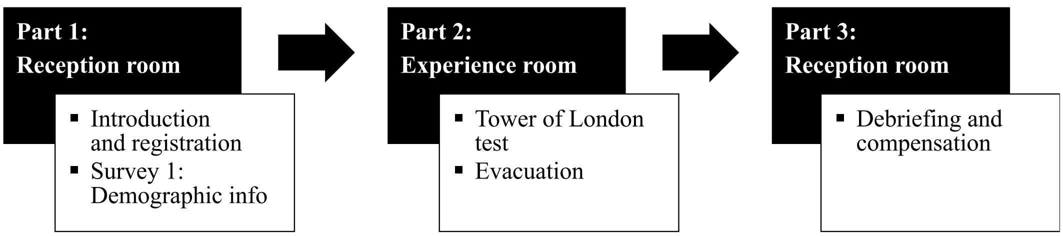

Fig. 3. Overview of the used materials and the procedure in the experiment.

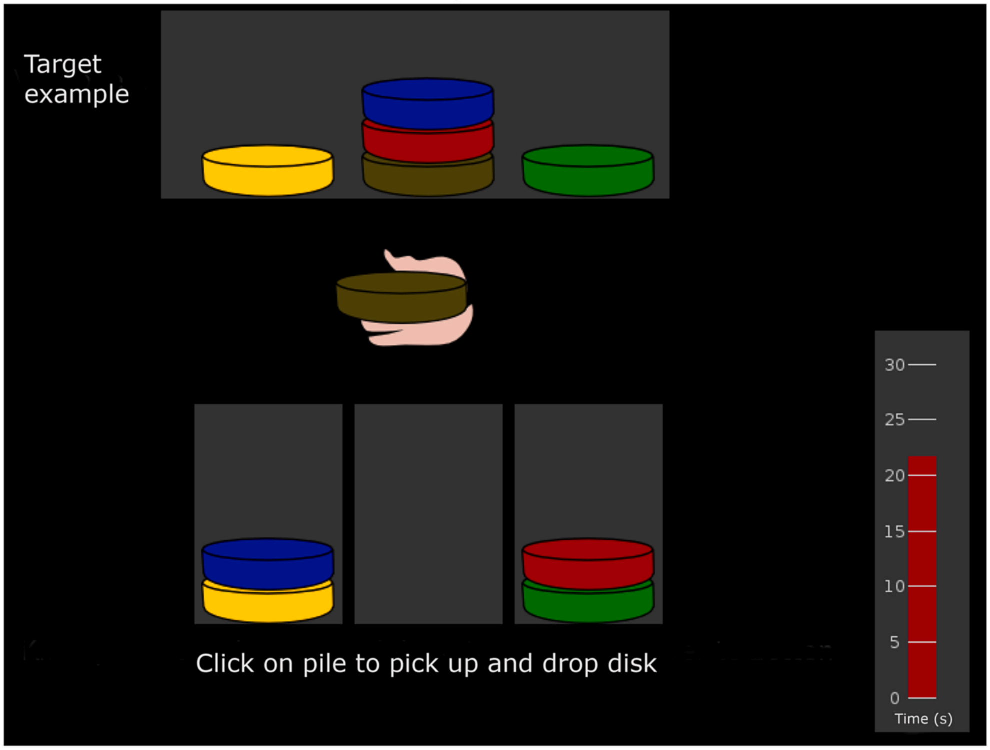

Fig. 4. Screenshot from Tower of London test (English translation).

Table 2
Minimum moves of the eight Tower of London trials.

Tower of London trials	Minimum moves
Trial 1	3
Trial 2	5
Trial 3	6
Trial 4	7
Trial 5	8
Trial 6	9
Trial 7	9
Trial 8	11
Minimum total moves	58

2.4.2. Video recordings: evacuation time

In the experience room, the evacuation time of the participants was recorded by four infra-red cameras. To identify the participants afterwards, the participants wore a reflecting band. In case of a maximum of five participants in an experiment, the first participant wore the band on the left upper arm, the second on the left forearm, the third on the right upper arm, the fourth on the right forearm and the last participant could then be identified by not wearing a band at all. The measured evacuation time was the time between the moment the participant got up from his or her seat after completion of the Tower of London test and the moment the participant stepped through the last door opening (‘door 4’) in the fourth compartment (see Fig. 1).

2.4.3. Two surveys

During the study two surveys were administered on a laptop. The first survey was completed *before* the evacuation experiment in the experience room. This survey collected biographical information (gender, age). The second survey was completed *after* the evacuation experiment in the experience room. In this survey the participants reported various personal experiences. However, the results of this second survey are not discussed in this paper.

2.5. Procedure

The participants were welcomed in the reception room, where they received (1) a document including information about the procedure of the experiment and (2) an informed consent form. After reading the information document, the participants were asked to sign the informed consent form if they understood and agreed with the content of the information document. After this, they completed the first survey. Next, the participants were escorted by the researchers to the control room of the experience room. The mobile phones of the participants were collected or turned off and the reflecting bands (see section 2.4.2) were distributed. Also, the researchers provided the participants with safety instructions. In case one of the participants did not feel comfortable in the experience room or did not want to participate anymore during the experiments, they were instructed to put both arms in the air. In that case, the researchers in the control room would immediately stop the experiment. After giving these instructions, the participants were escorted to the central room of the experience room. Here, the participants received information about the Tower of London test. The participants were instructed that they, individually, were only allowed to evacuate the room and to find a way out of the experience room after they completed this test. They were also instructed not to use the door through which they entered the room. They had to find another way out of the experience room. Finally, the researchers told the participants that there was a present available in the control room for the person who successfully managed to evacuate the experience room first of his/her group. This was done to stimulate the participants to evacuate the experience room as soon as possible. At the moment the researcher left the central room, another researcher started one of the experimental scenarios or did nothing in case of the control scenario. After the experiment in the experience room, the participants were immediately escorted to the reception room where they completed the second survey.

2.6. Data analyses

The data was analysed with IBM SPSS Statistics (Version 29). The graphics were generated using DataGraph (Version 5.3.1β) [22].

In section 3.1 between subjects ANOVAs were conducted for the effects of the three environmental factors (evacuation scenarios), age and gender on problem-solving abilities. For the age-related analyses, participants were divided into six age categories (see section 3.1.1). Although the number of participants per evacuation scenario and/or age category differ, we chose ANOVAs for our analyses and performed sensitivity analyses using G*Power 3.1.9.6 for Mac [23]. For the one-way ANOVAs for evacuation scenario respectively age category, sensitivity analyses indicated that with a sample size of 147, 80% power, a Type I error rate of 5% (two-sided) and 4 respectively 6 groups, effect sizes of Cohen's $f = 0.27$ respectively Cohen's $f = 0.30$ can be detected. These effect sizes equal partial eta squared values of approximately 0.06 respectively 0.08, which are medium effects [24]. For the two-way ANOVAs for evacuation scenario × gender, a sensitivity analysis indicated that with a sample size of 147, 80% power, a Type I error rate of 5% (two-sided) and 8 groups, an effect size of Cohen's $f = 0.27$ can be detected. This effect size equals a partial eta squared value of approximately 0.06, which is a medium effect [24]. For the post hoc analyses, Gabriel comparisons are given. These comparisons control the familywise error by correcting the level of significance for each test such that the overall Type I error rate across all comparisons remains at 0.05. The mentioned effect sizes are partial eta squared. As proposed by Cohen [24] the guidelines for interpreting (partial) eta squared effect sizes are: 0.01 = small effect, 0.06 = medium effect and 0.14 = large effect.

In section 3.2 Pearson correlation analyses were conducted to investigate the relationships between the problem-solving abilities and building evacuation time per evacuation scenario.

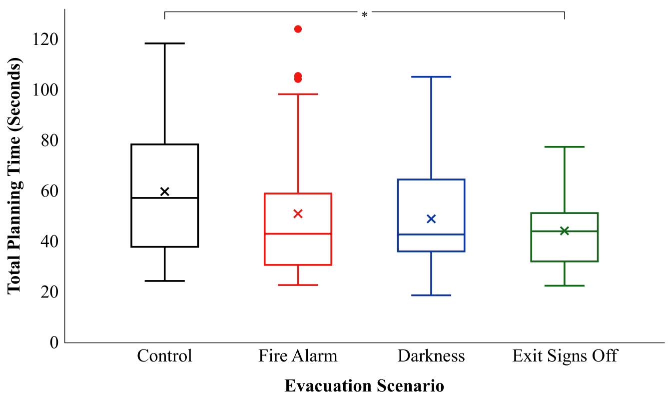

Fig. 5. Total planning time on Tower of London test per evacuation scenario.
$^*p < .05$.

3. Results

In the following sections the results of the experiments are presented per research question (see section 1).

3.1. The effects of three environmental factors on problem-solving abilities during evacuation

In this section, the effects of the three environmental factors on the Tower of London test performance during evacuation are reported. The two dependent measures for the Tower of London test are (1) the *total planning time*, i.e. the time between seeing the discs on the computer screen and making the first move, for all eight trials together and (2) the *total number of excess moves*, i.e. how many moves more than the minimum moves were necessary to complete all eight trials. In addition, the effects of age and gender on these problem-solving abilities are analysed.

3.1.1. Effects of the environmental factors on total planning time tower of London test

The first dependent measure for the Tower of London test is the *total planning time* (the time between seeing the discs on the computer screen and making the first move, for all eight trials together). A one-way ANOVA revealed that there was a significant effect of the environmental factors on the total planning time at the $p < .05$ level, F (3, 143) = 3.04, $p = .031$, partial $\eta^2 = 0.06$, a medium effect. The more environmental factors were added to the evacuation scenario, the less planning time participants needed or took. The post hoc tests revealed a significant difference at the $p < .05$ level between the control and exit signs off scenario, $p = .019$, 95% CI [1.69, 29.35] (see Fig. 5). Participants in the exit signs off scenario needed or took on average 15.5 s less – a decrease of 25.9% – to plan their actions in the Tower of London test than participants in the control scenario. This means that the combination of a fire alarm, darkness and not illuminated emergency exit signs had a negative influence on planning time, compared to the control scenario. The other comparisons were not significantly different (control – fire alarm, $p = .454$ [−5.23, 22.76], control – darkness, $p = .206$ [−2.95, 24.56], fire alarm – darkness, $p = .999$ [−10.65, 14.72], fire alarm – exit signs off, $p = .645$ [−6.01, 19.52], and darkness – exit signs off, $p = .896$ [−7.80, 17.24]).

For the additional age effect analyses, the participants were divided into six age categories according to their age. The ratio of the distribution of the participants in these age categories over the four scenarios was not significantly different, χ^2 (15) = 11.92, $p = .685$ (see Figure B.1 in Appendix B for the distribution of the participants in the age categories over the four scenarios). Per scenario there were not enough participants in the different age categories to compare the planning time of these participants. However, it was possible to analyse if age category had an overall effect on total planning time. A one-way ANOVA demonstrated that there was a significant effect of age category on the total planning time at the $p < .001$ level, F (5, 141) = 19.93, partial $\eta^2 = 0.41$, a large effect. The post hoc tests revealed in total nine significant differences: six at the $p < .001$ level, one at the $p < .01$ level and two at the $p < .05$ level (see Fig. 6). For legibility reasons, the outliers are not included in Fig. 6. In Figure B.2 in Appendix B the same figure is displayed *with* outliers, but *without* the significant post hoc results. Age category 18–25 years differed significantly with the three oldest age categories. The biggest difference was between age categories 18–25 years and 66–78 years: the oldest participants took or needed 42 s more planning time than the youngest participants, an increase of 146.9%. This suggests that the youngest participants reacted very quickly in the Tower of London test and did not need or took much time to plan their actions. Age category 26–35 years also differed significantly with the three oldest age categories. Age category 36–45 years differed significantly with the two oldest age categories. Finally, age category 46–55 years differed significantly with the oldest age category. These results suggest that at least as of 46 years participants needed or took substantial more planning time than younger participants.

For the additional gender effect analyses, it was possible to compare the planning time of men and women per evacuation scenario. The ratio of the distribution of men and women over the four scenarios was not significantly different, χ^2 (3) = 1.70, $p = .638$. A two-

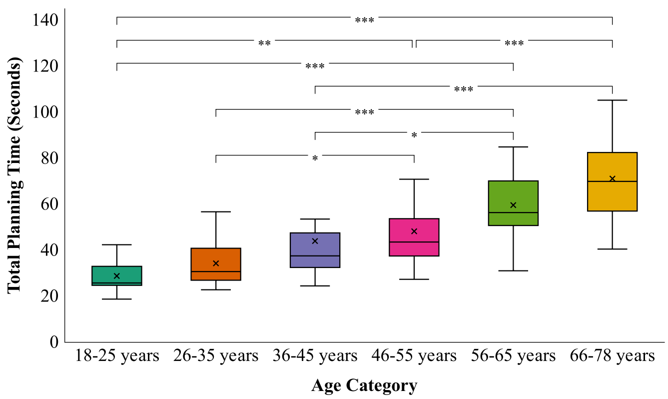

Fig. 6. Total planning time on Tower of London Test per age category.
*$p < .05$. **$p < .01$. ***$p < .001$.

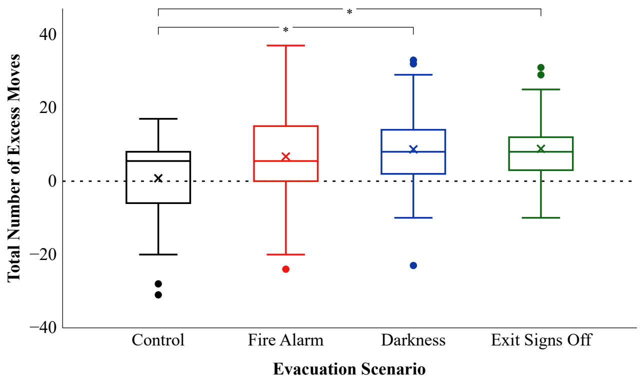

Fig. 7. Total number of excess moves of Tower of London test per evacuation scenario.
*$p < .05$.

way ANOVA revealed, again, a significant main effect of the environmental factors on the total planning time at the $p < .05$ level, F (3, 139) = 2.82, p = .041, partial η^2 = 0.06, a medium effect. The post hoc tests revealed, again, a significant difference between the control and exit signs off scenario at the $p < .05$ level, p = .020, 95% CI [1.61, 29.44]. The other scenarios comparisons were not significant. However, there was no main effect of gender on total planning time, F (1, 139) = 0.00, p = .973. Hence, men and women did not differ significantly on total planning time. The interaction effect between the evacuation scenario and gender was not significant either, F (3, 139) = 0.76, p = .518.

3.1.2. *Effects of the environmental factors on total number of excess moves tower of London test*

The second dependent measure for the Tower of London test is the *total number of excess moves*, i.e. how many moves more than the minimum moves were necessary to complete all eight trials (see also Table 2). There was a significant effect of the environmental factors on the number of excess moves at the $p < .05$ level, F (3, 143) = 3.39, p = .020, partial η^2 = 0.07, a medium effect. As shown in Fig. 7 the participants in the darkness and exit signs off scenarios had the most excess moves, more than eight. There were also participants who had less moves than the minimum moves required to solve the trials. This means that they were not able to solve the trials in 30 s per trial. The post hoc tests revealed significant differences at the $p < .05$ level between the control and darkness scenario, p = .031, 95% CI [−15.31, −0.48], and between the control and exit signs off scenario, p = .028 [−15.50, −0.58] (see Fig. 7). Participants in the darkness scenario had on average almost eight more excess moves than participants in the control scenario. This means that the combination of a fire alarm, darkness and illuminated emergency exit signs had a significant effect on total excess moves, compared to the control scenario. Participants in the exit signs off scenario also had on average eight more excess moves than participants in the control scenario. This means that the combination of a fire alarm, darkness and not illuminated emergency exit signs also had a significant effect on total excess moves, compared to the control scenario. Hence, the combination of a fire alarm and darkness seems to have the most effect on the number of excess moves. The other comparisons were not significantly different (control – fire alarm, p = .202 [−13.50, 1.59], fire alarm – darkness, p = .971 [−8.79, 4.89], fire alarm – exit signs off, p = .961 [−8.97, 4.79], and darkness – exit signs off, p = 1.000 [−6.89, 6.61]).

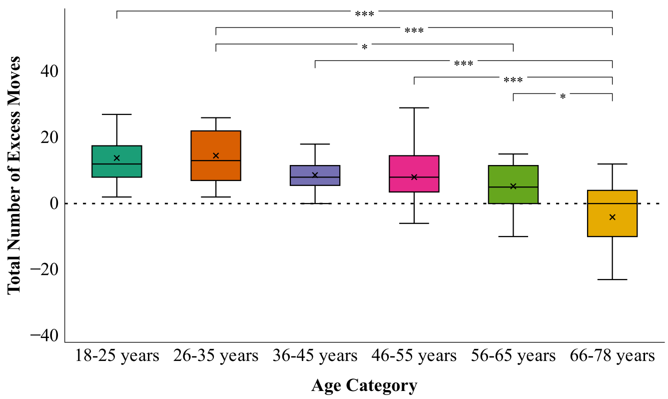

Fig. 8. Total number of excess moves of Tower of London test per age category.
*$p < .05$. ***$p < .001$.

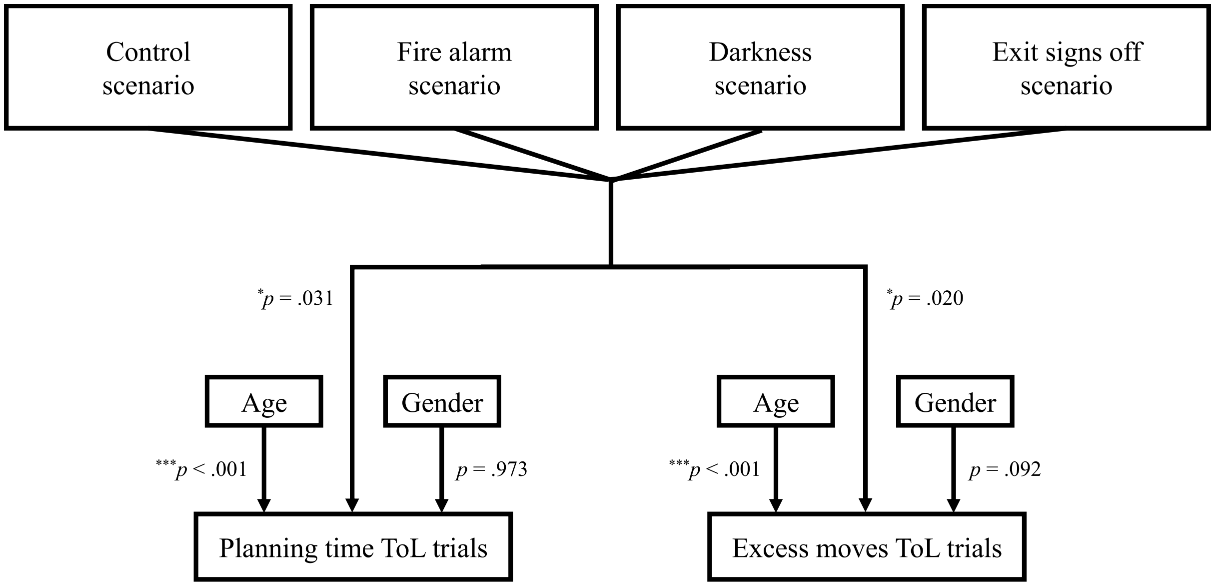

Fig. 9. Effects of evacuation scenarios, age and gender on problem-solving abilities.
Note. ToL = Tower of London. *$p < .05$. ***$p < .001$.

For age category, a one-way ANOVA revealed that there was a significant effect of age category on the total number of excess moves at the $p < .001$ level, $F\,(5, 141) = 11.09$, partial $\eta^2 = 0.28$, a large effect. The post hoc tests revealed in total six significant differences: four at the $p < .001$ level and two at the $p < .05$ level (see Fig. 8). For legibility reasons, the outliers are not included in Fig. 8. In Figure B.3 in Appendix B the same figure is displayed *with* outliers, but *without* the significant post hoc results. The older the participants, the less excess moves they had. In fact, on average the older participants had even less moves than the 58 minimum moves that were required to solve all eight Tower of London trials. The two youngest age categories had the most excess moves. The oldest age category differed significantly from all other age categories. The biggest difference was between age categories 26–35 years and 66–78 years, a difference of more than 18 excess moves.

For gender, a two-way ANOVA revealed, again, a significant main effect of the environmental factors on the total number of excess moves at the $p < .05$ level, $F\,(3, 139) = 3.18$, $p = .026$, partial $\eta^2 = 0.06$, a medium effect. The post hoc tests revealed, again, significant differences at the $p < .05$ level between the control and darkness scenario ($p = .031$, 95% CI [−15.33, −0.46]) and between the control and exit signs off scenario ($p = .028$ [−15.51, −0.57]). The other scenarios comparisons were not significant. However, there was no main effect of gender on total number of excess moves, $F\,(1, 139) = 2.87$, $p = .092$. Hence, men and women did not differ on the total number of excess moves. The interaction effect between the environmental factors and gender was not significant either, $F\,(3, 139) = 0.33$, $p = .804$.

In Fig. 9 the results of all the ANOVAs discussed in sections 3.1.1 and 3.1.2 for the effects of the evacuation scenarios, age and gender on the two measured problem-solving abilities are depicted.

3.2. Relationships between problem-solving abilities and building evacuation time

In this section, the relationships between the problem-solving abilities and building evacuation time are investigated. For this purpose, Pearson correlation analyses were conducted. In these analyses, five participants of the Tower of London test were excluded because no valid evacuation time registration was available for them. In Table 3 and Fig. 10 the results of the correlation analyses between building evacuation time and the measures of the Tower of London test are presented per evacuation scenario.

There was a significant *positive* correlation between the total planning time and building evacuation time for the participants in the exit signs off scenario, $r = 0.44$, $p = .005$, 95% CI [0.14, 0.66]. This indicates that the more planning time the participants in the exit

Table 3
Correlations between building evacuation time and Tower of London measures per evacuation scenario.

Building evacuation time	*n*	*M*	*SD*	Planning time	Excess moves
Control scenario	27	31.44	7.01	0.37	−0.24
Fire alarm scenario	37	30.54	12.68	0.17	−0.08
Darkness scenario	39	34.95	11.17	−0.10	0.14
Exit signs off scenario	39	38.21	15.59	0.44**	−0.36*

*$p < .05$. **$p < .01$.

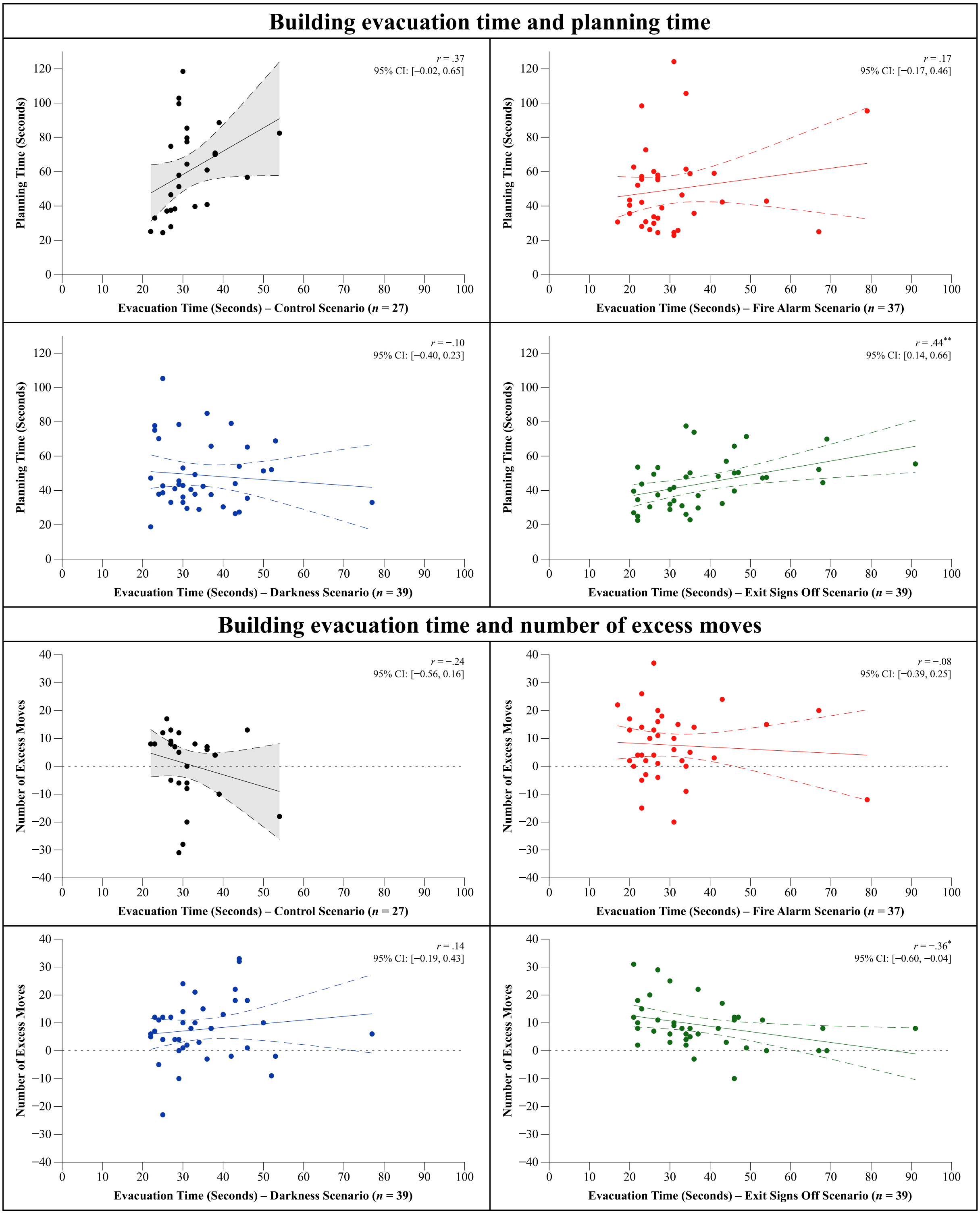

Fig. 10. Correlations between building evacuation time and Tower of London measures per evacuation scenario.
$^{*}p < .05$. $^{**}p < .01$.

signs off scenario took or needed, the longer their evacuation time was. Also, there was a significant *negative* correlation between the total excess moves and building evacuation time for the participants in the exit signs off scenario, $r = -0.36$, $p = .026$ [−0.60, −0.04]. This indicates that the more excess moves the participants in this scenario had, the less time they needed to evacuate the room. An additional correlation analysis between planning time and number of excess moves revealed a significant *negative* correlation at the $p < .001$ level, $r = -0.738$ [−0.80, −0.65]. This means that longer planning times were indeed associated with fewer excess moves.

4. Discussion

The first research focus of this study was to investigate the effects of three environmental factors (fire alarm, lighting and emergency exit signs illumination) on problem-solving abilities during evacuation and compare these with a control scenario. In the control scenario there was no activated fire alarm, the lighting conditions were normal and the emergency exit signs were illuminated. The conditions of the three experimental evacuation scenarios were: (1) a fire alarm, normal lighting conditions and illuminated emergency exit signs (fire alarm scenario), (2) a fire alarm, a dark environment and illuminated emergency exit signs (darkness scenario) and (3) a fire alarm, a dark environment and *not* illuminated emergency exit signs (exit signs off scenario). The main results indicate that the combination of a fire alarm, darkness and not illuminated emergency exit signs significantly reduced the planning time of the participants, compared to normal conditions. In addition, the combination of a fire alarm, darkness and illuminated emergency exit signs respectively the combination of a fire alarm, darkness and not illuminated emergency exit signs also significantly increased the number of excess moves, compared to normal conditions. Another important finding is that age had a significant effect on the two problem-solving abilities. At least as of 46 years participants needed or took substantial more planning time than younger participants. Also, the older the participants, the less excess moves they had. For gender no significant effects on problem-solving abilities were found.

The second research focus of this study was to investigate the relationships between problem-solving abilities and building evacuation time. In the scenario with an activated fire alarm, darkness and not illuminated emergency exit signs, there seems to be a significant relationship between problem-solving abilities and building evacuation time. The more planning time participants took or needed in this scenario, the longer their evacuation time on average. Also, the more excess moves participants had, the less time they needed to evacuate the room on average.

These results and their implications are discussed in more detail in the following sections.

4.1. Discussion results

4.1.1. Effects environmental factors, age and gender on problem-solving abilities

The exit signs off scenario significantly affected planning time, compared to the control scenario. The three environmental factors led to a decrease of 25.9% in planning time. Also, the darkness and exit signs off scenario both significantly affected the number of excess moves, compared to the control scenario. In both scenarios, the environmental factors led to, on average, eight more excess moves.

In summary, when participants were confronted with the three environmental factors, they took significantly less time to plan their actions. It seems that these participants were more inclined to act instead of think compared to the participants in the control scenario. This also explains why the participants who were confronted with (two of) the three environmental factors also had more excess moves compared to the participants in the control scenario. Again, they seem to be more focused on 'doing' (i.e. moving discs) instead of 'thinking' (i.e. assess the problem and plan an action). These results show how complex planning and problem-solving is in emergency conditions. On the one hand, people need time to assess the situation and the environment and on the other hand, in emergencies time is of the essence and people seem to be more inclined to just do something instead of thinking about their actions.

In the literature, no studies were found in which the same evacuation conditions were used, but there are some studies available with comparable distractable conditions. In two studies in which four different types of secondary tasks were examined in combination with the Tower of London task, it was found that planning time was significantly reduced when the task was performed with any of the four secondary tasks [16,25]. Also, secondary tasks resulted in more moves being made than in single-task conditions [25]. In our study similar results were found: when participants were distracted with a fire alarm, darkness and not illuminated exit signs, participants had longer planning times and more excess moves compared to the control condition. In the earlier mentioned simulated aircraft disaster study, Cassidy [1] found a trend of increased problem-solving scores as survival likelihood increased. Those who were more likely to 'survive' the simulation had significantly higher problem-solving style scores. This means that individuals who tended to be creative in problem-solving and tackled problems head on, had a better chance in the survival situation than individuals without this problem-solving style. For emergency evacuation situations this could mean that individuals with effective problem-solving abilities might be more self-sufficient compared to individuals with poor problem-solving abilities.

Another significant finding in our study is that age influenced the two problem-solving abilities. As of 46 years participants needed or took substantial more planning time than younger participants. Similar age effects on planning time have been found in other studies. Andrés and Van der Linden [26] found that participants aged 60–70 years took more planning time than participants aged 20–30 years. McEwan [27] compared age groups 18–30 years and 60–85 years. Participants in the older group had longer planning times than participants in the younger group. In the study of Gilhooly et al. [28] the planning time of older participants (60–76 years) was less complete and more error-prone than that of younger participants (17–25 years). In addition, in our study the oldest age category differed significantly from all other age categories on the number of excess moves: the older the participants, the less excess moves they had. However, previous studies found contradictory results in this respect. In the earlier mentioned study of Andrés and

Van der Linden [26], participants aged 60–70 years made significantly more moves to solve the problems than participants aged 20–30 years. Bugg et al. [29] also found a significant age-related increase in the number of excess moves. That in our study older participants had *fewer* excess moves than younger participants is probably because in our study a timer of 30 s was used to solve each problem. It is possible that in a Tower of London test without a timer, older participants would have more excess moves than younger participants. Therefore, this result should be interpreted with caution.

Finally, in our study no significant gender effects on problem-solving abilities were found. Previous research in this respect shows inconsistent results. In a study with six different age categories men and women differed on planning time in two of the six age categories: in age category 15–25 years women were slower than men but in the age category 26–35 years they were faster than men [30]. Another study showed that the fifth decade of life possibly marks a critical age (as of 45 years) at which gender differences on planning performance begin to emerge [31]. McEwan [27] found no gender effects on problem-solving abilities. Therefore, more research on this topic is needed.

4.1.2. Relationships between problem-solving abilities and building evacuation time

There seems to be a relationship between problem-solving abilities and building evacuation time. In the exit signs off scenario, there was a *positive* correlation between planning time and evacuation time. The more planning time the participants took or needed in this scenario, the longer their evacuation time was. This seems logical: if building occupants are confronted with problems or obstacles during an evacuation, they have to assess the situation and environment and come up with a plan of action. This takes time and therefore the evacuation is probably delayed. For number of excess moves, there was a *negative* correlation in the exit signs off scenario. This suggests that the more excess moves the participants had in this scenario, the less time they needed to evacuate the room. Participants with more excess moves seem to be focused on finishing the task as quickly as possible by taking action instead of thinking. In addition, our study revealed a significant *negative* correlation between planning time and number of excess moves ($r = -0.738$). However, Phillips et al. [32] found a significant *positive* correlation between planning time and number of excess moves ($r = 0.56$). Again, our results should be interpreted with caution. They are probably influenced by the fact that in our study a timer was used in the Tower of London test.

Furthermore, it seems that solving problems usually requires some creativity. In the earlier mentioned simulated aircraft disaster study, a significant correlation was found between speed of egress and problem-solving score [1]. Those who exited the aircraft faster, had a more positive problem-solving style. These participants were more confident and creative and they were more likely to approach problems instead of avoiding them [1]. In a study of a real disaster, the 2011 Great East Japan earthquake and tsunami, significant positive associations were found between problem-solving and immediate evacuation respectively survival success in refugee situations [33]. Hence, a creative problem-solving style could be advantageous for emergency evacuations and survival. Therefore, more research into the possible relationships between the mutual problem-solving abilities is needed but also between problem-solving abilities and building evacuation behaviour.

4.2. Strengths, limitations and future research

A strength of our study was the focus on problem-solving abilities in different environments because there are not a lot of studies done in this respect. Therefore, it is highly recommended to do more research on this topic. Not only should this be done in experimental settings, but also more research is needed on what problem-solving abilities and styles people use in real emergencies and how these abilities and styles might be related to survival in different environments. For instance, as was done in the study of Sugiura et al. [33]. Another strength of our study was the diverse group of participants. They came from the local community and were from all walks of life with a broad age range.

A limitation of this study is that the participants were not inquired about their computer (mouse) use and/or computer (gaming) experience in daily life. It might be possible that if participants had limited computer experience, this affected their performance on the Tower of London test. The age-related effects and associations could perhaps be partly explained by a lack of computer experience, as also suggested by McEwan [27]. However, in a study in which a real tower test was used and not a computer version, also age-related differences were found [34]. Another limitation was that the age categories per scenario were not evenly distributed, although the distribution in our study was not significantly different. However, for future research it is recommended to distribute the different age categories more evenly over the different scenarios. A further limitation of our study is that the participants were not surveyed about any previous evacuation experience, either for real incidents or for drills. For future research, it is advised to include these questions.

The Tower of London test is commonly used in neuropsychological assessments [35]. However, the use of this test in emergency and survival experiments is not so common. Besides the use in our experiment and to the knowledge of the authors, this test has previously only been used by Porter and Leach [14] in an intensive military survival experiment. Although this test does not literally represent a task building occupants are likely to perform during an evacuation, this test does provide evidence to suggest that individuals exposed to challenging environmental factors in survival situations experience impairments in planning and action components of the Tower of London test [14]. However, more studies with this test are required. Therefore, for future research we recommend to include the Tower of London test as a measurement for planning and problem-solving abilities in challenging emergency and/or survival experiments. In addition, it is advised to not set a timer on the Tower of London test in order to investigate how many excess disc moves participants really need to solve the trials, especially older participants.

Finally, in our study gender effects on problem-solving abilities in different environments were not found. Therefore, it is recommended to do more research in this respect because earlier research shows inconsistent results about possible gender differences [27,30].

4.3. Practical and theoretical implications

A practical implication of our findings is that problem-solving abilities seem to be affected in evacuation conditions where several environmental factors are increasingly added. The more distracting the environmental factors seem to be, the less time participants took or needed to plan their actions. Problem-solving in a dark environment was more difficult than in an illuminated environment. Also, longer planning times were associated with longer evacuation times. A practical implication is that building and safety managers could already use this knowledge in evacuation plans and drills. For example, not only activating a fire alarm in an evacuation drill but also adding darkness to the environment or perhaps even doing such drills at night. Furthermore, building occupants could be trained and educated on how to be prepared for emergencies so that they can act swiftly in evacuation situations. This is even more relevant in buildings with older populations.

A theoretical and methodological recommendation for future research is to further investigate the effects of psychological stressful environmental factors on problem-solving abilities. This could be done by adding other problem-solving tests or complex tasks. In experimental designs also obstacles on escape routes could be added to replicate more real emergencies. Of course, this should be done within ethical boundaries. Furthermore, the relationships between building evacuation time and personal characteristics such as problem-solving styles, age and gender should be studied in more depth. These factors are rarely investigated but our findings suggest that this could be relevant for, for instance, evacuation simulation models. With this information incorporated in simulation models, prediction of behaviours might become more realistic.

5. Conclusions

Our findings suggest that environmental factors such as a combination of a fire alarm, darkness and not illuminated emergency exit signs significantly affect planning time. Under these conditions, participants needed or took much more planning time than in normal conditions. That is also the trade-off here: in building emergency situations occupants need time to assess the situation and the environment, and think of a plan of action but in emergencies time is usually of the essence. For this reason, preparation and training for building emergencies is crucial. This is especially relevant for older populations, because our findings suggest that they need or take much more time to plan their actions, compared to younger populations. Therefore, safety managers of buildings with older populations, such as nursing homes, should assume longer evacuation times. It will be interesting to further investigate the effects of various environmental factors on planning time and problem-solving abilities during an evacuation. Not by using a computer test, but by adding a real obstacle or problematic situation on the escape route, of course within ethical boundaries. If these results can be quantified, this could be useful input for evacuation simulation tools. Furthermore, it is highly recommended for future research to include investigations into the possible effects of personal characteristics such as problem-solving styles, age and gender in studies about evacuation behaviour and building evacuation times. If there is more quantifiable information available in this respect, probably more realistic predictions can be made about building evacuation times for building occupants. Although our findings warrant more research, building and safety managers can already take the findings of this study into account in evacuation plans and drills by adding training in darkness scenarios or assuming more evacuation time in darkness or for older aged populations.

CRediT authorship contribution statement

Erica Kinkel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **C. Natalie van der Wal:** Writing – review & editing, Visualization, Formal analysis. **Serge P. Hoogendoorn:** Writing – review & editing, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Photos of the lighting conditions in the experience room in the control, fire alarm, darkness and exit signs off scenarios.

1. Central room	2. Corridor 1	3. Corridor 1	4. Corridor 2	5. Corridor 2	6. Dead end room	7. Corridor 3

Control and fire alarm scenario

Darkness scenario

Exit signs off scenario

Appendix B

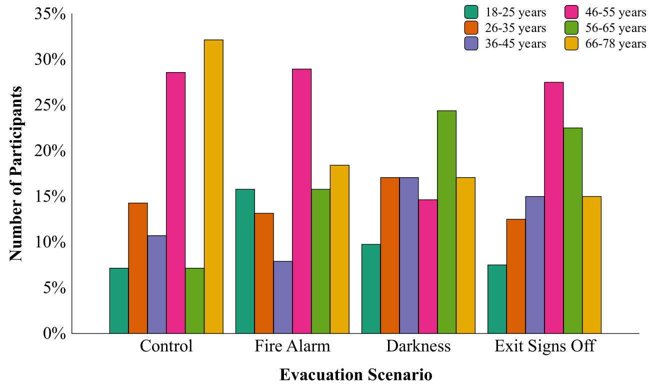

Fig. B.1. Number of participants per age category per evacuation scenario.

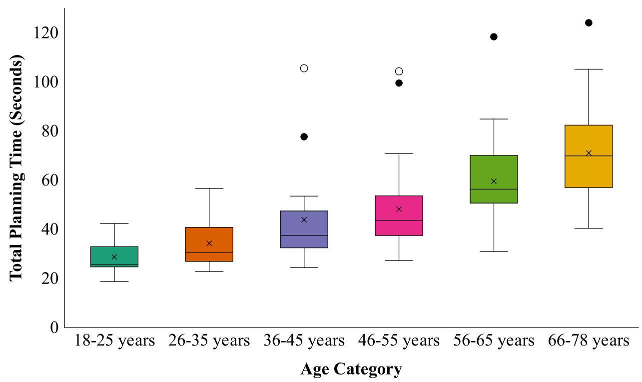

Fig. B.2. Total planning time on Tower of London test per age category (with outliers).

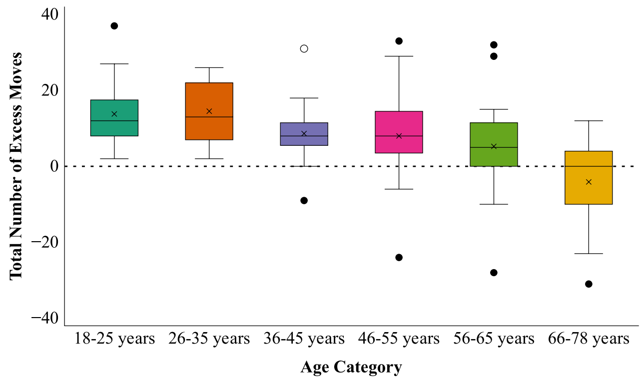

Fig. B.3. Total number of excess moves of Tower of London test per age category (with outliers).

Data availability

Data will be made available on request.

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