Team Situation Awareness in Firefighting: The Impact of Sudden Obstructions, Building Complexity and Information Availability

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by

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Abstract

This study explored the effects of architectural legibility (spatial complexity), information status, and sudden obstructions on team situation awareness (TSA) and team performance in an indoor firefighting setting. Twenty-one dyads of students searched for fires and victims in four virtual reality simulations of fire scenarios. Surprisingly, teams performed overall better in the building which had a lower level of architectural legibility (higher spatial complexity), but complete information status was overall associated with higher TSA scores. Generally, team performance also deteriorated after participants encountered an unexpected obstruction during the scenario. The better performance in the setting of low architectural legibility pointed to the importance of visibility and field of view of a space, implying the significance of spatial complexity parameters in team performance and situation awareness.

Keywords: team situation awareness, architectural legibility, firefighting, workload shift, information sufficiency, virtual reality simulation

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Sudden Obstructions, Building Complexity, and Information Availability in Firefighting Teamwork

In 2001, Canadian fire departments dealt with 55,300 fire emergencies that claimed 337 lives, injured 1,754, and cost $1.421 billion dollars in property loss (Hall, 2005). In the US alone, fires result in more civilian deaths than all other natural disasters combined, where each year 4,000 victims are killed and 25,000 are injured (Jiang, Takayama, & Landau, 2004). On average, residential fires account for 71 % of all fire-related fatalities and cause over 40% of property damages in Canada (CCFMFC, 2002). Civilians and their properties are not the only casualties of fire incidents. Every year, 100 American firefighters die in the line of duty (Jiang et al., 2004) and between1848 to 2010, 1,000 Canadian firefighters have sacrificed their lives doing their job (Canadian Press, 2010, para. 1). In addition, close to half or 45.4 % of injuries which firefighters suffer take place during the fire operation (Karter & Molis, 2011).

As can be seen from the statistics mentioned above, firefighting is a highly hazardous occupation. In such dynamic, time-pressured situations, firefighters often do not have the time to meticulously compare various possible solutions and arrive at an optimal decision. Instead, they typically resort to matching the emergency at hand with previous incidents from experience and to employing the appropriate decision in order to save time (Fern et al., 2008). The personnel may even be forced to act before there is enough information to achieve the primary goals of saving lives and property. However, executing decisions without having a "big picture" of the incident should be avoided whenever possible because, when the situation unexpectedly changes, there is little time to formulate alternative strategies (Ottawa Fire Services, 2010). Therefore, the firefighting process is more efficient with greater availability of the relevant information.

The two primary goals of firefighting are to save lives and prevent property loss as much as possible (Ottawa Fire Services, 2010). Fern et al. (2008) further divided these main goals into several sub-goals, one of which is situation assessment. Situation assessment is known as the process by which one arrives at a state of situation awareness, or knowing "what is going on around you" (Endsley, 2000). Situation awareness was initially studied within the context of the aviation industry, but it has been studied in other fields with dynamic environments such as military operations, air traffic control, healthcare, and football (Uhlarik & Comerford, 2002). One of the decisions to be made with situation assessment is where to search for the fires' locations within the structures. One of several pieces information relevant to locating the fires is the floor plan of the building, which, in turn, is crucial for another firefighting sub-goal of route management. With the proper route management, fire crews can find the safest and most efficient means to reach and combat the fire hazards (Fern et al., 2008).

The literature presented thus far suggests that the factors of situation awareness, information status, spatial properties of the buildings, and unexpected changes in such emergencies are interconnected with each other. The present study thus aimed to further investigate the relationship amongst these factors. Given the ever-present danger inherent in firefighting, it is only appropriate that an empirical research study be conducted on the teamwork dynamics of firefighting crews in order to make a positive contribution to this domain. In this chapter, I will first review the concept of situation awareness, specifically as it pertains to the teamwork setting. The subsequent sections will then explain how TSA affects performance and interacts with workload, followed by discussions on workload shift and architectural legibility.

Situation Awareness

Situation Awareness (SA) is defined as "the perception of the elements in the environment within a volume of time and space, comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1988, p. 97). The perception, comprehension, and projection in the definition reflect the three levels of SA (Levels 1, 2, and 3, respectively) where a lower level must be reached before proceeding to the next, higher level of awareness. However, arriving at a higher SA level can inform the worker about the nature of SA at the lower level through feedback. One can use a puzzle analogy to understand the meaning of the SA levels. Level 1 SA (perception) is about perceiving the puzzle pieces of the information in the environment, while level 2 SA (comprehension) refers to the integration of the critical information cues to extract meaning and can be compared with fitting the pieces of a puzzle together. From the integration of that information, one can project how the situation will unfold in the future (level 3 SA).

The conceptualization of SA was subject to debate when it was first introduced as a construct (Sarter & Woods, 1991; Flach, 1995). Endsley's abovementioned definition is the most popular and accepted because of the clear-cut distinction into the three stages (Sorensen et al., 2011). However, subject matter experts often cannot deconstruct their SA neatly into its three levels (Klein, 1998). Moreover, there was also a disagreement as to whether SA is a cognitive product or a process (Adams et al., 1995; Salas et al., 1995). In other words, is SA a snapshot of the operator's picture of the situation model (product) or is it the process by which one arrives at that picture? Smith and Hancock (1995) argue that Endsley's three-level definition refers to SA as both the product and process, both of which which are interdependent on each other in a continuous perception-action cycle (Gorman, Cooke, & Winner, 2006).

According to Neisser's perception-action cycle (1976), the knowledge of the operator residing in his/her long-term memory directs the perceptual exploration of the environment (i.e., the action). The action of perceptual exploration gives the operator a picture of the ongoing activity, which in turn modifies the knowledge of the operator. Given the dynamic nature of the situation, the individual's situation awareness is adaptively updated through this cycle according to the goal of the task (Smith & Hancock, 1995).

Although SA is a concept initially popular in the aviation field, it has since become a factor that is critical to understanding performance in other complex, dynamic domains such as air traffic control, healthcare, military and space operations, maintenance, power plants (Endsley, 1995b), and also firefighting (Martin & Flin, 1997). The importance of SA cannot be underestimated as Hartel, Smith, and Prince (1991) found poor SA to be the leading cause of pilots' errors in controlling military aircraft, and Endsley (1994) found that 88% of pilot errors committed while operating commercial airplanes could be attributed to a deficient SA. Within the context of firefighting, the significance of SA is evident in the need for firefighters to assess as much relevant information as possible that can help them save lives and property. For instance, firefighters need to know wind direction and the location of trapped building residents (perception of critical elements-Level 1 SA) because if the wind, for example, blows from the east and the victims are on the west side of the building, they can conclude that fire is headed towards the victims (level 2 SA-comprehension), and unless they execute the plan to extinguish the fire and/or evacuate the people, lives will be lost (level 3 SA-projection).

Endsley (1995a) hypothesized that, while situation awareness predicts performance, the link between the two constructs is probabilistic. An operator can have perfect SA and still perform poorly, while another operator with degraded SA may perform flawlessly in some automated circumstances (Adams et al., 1995). High SA does not necessarily guarantee better performance; with higher SA the operator is likely to perform better because there are factors other than SA that could also influence performance significantly. For instance, Durso and Gronlund (1999) argued for the importance of domain-specific knowledge and that, without sufficient knowledge, operators can misinterpret the situation at hand. In analyzing the SA requirements of infantry soldiers, Endsley, Holder, Leibrecht, Garland, Wampler, and Matthews (2000) listed and discussed how the quality of the military training program can either sharpen or worsen the soldiers' ability to extract information in the unpredictable battlefield environment. In support of Endsley et al.'s (2002) argument, O'Brien and O'Hara (2007) observed that attention management training significantly benefited the performance and the SA scores of people with low SA-ability scores in an air traffic control simulation game. Other studies generally support the positive correlation between SA and performance (Durso et al., 1999; Entin & Entin, 2000; Berggren et al., 2008).

The literature reviewed so far has covered the importance of SA at the individual level. The goal of the study to investigate SA in the collaborative context of the firefighting task requires to examine the concept in a team perspective. SA on the team level is discussed in the next section.

Team Situation Awareness

Workers in dynamic and high-risk environments, such as firefighters, have to operate in teams due to the complexity of their jobs. A team is defined as " a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership," (Salas, Dickinson, Converse, & Tannenbaum, 1992, pp 4). Due to the necessity of teamwork in firefighting operations, it is only logical to examine SA within a team context and to explore the concept of team SA.

Endsley (1995b) referred to team SA as the extent by which a person has the SA requirements as prescribed by his or her role/assignment within the team, independent of the aspects of SA that he or she may share with other team members. This means that in an ideal situation, the shared SA among team members is automatically addressed if all individuals have a complete knowledge of his or her own SA requirements. Others have defined it as "the sharing of a common perspective between two or more individuals regarding current environmental events, their meaning, and projected future" (Wellens, 1993, p 272), "coordinated perceptions and coordinated actions," (Gorman et al., 2006, p. 1314), and "at least in part the shared understanding of a situation among team members at one point in time," (Salas et al., 1995, p 131). Combining all of these definitions, team SA is composed of individual SA that corresponds to each person's role and responsibility, as well as the overlap among those individuals' SA.

The level of interdependence amongst the team members' roles/responsibilities determines the degree of common understanding afforded by their shared SA. That is, the individuals' SAs need to be similar, to a certain degree, because ultimately they work toward the same collective goal, but the different responsibilities that different teammates have mean that it is unnecessary for their SA to be perfectly identical. Of course, the more similar the roles and responsibilities of the teammates are, the higher is the overlap of their shared SA. For instance, Sulistyawati , Wickens, and Yoon (2009) found a significant correlation between the SA of an individual and the same individual's estimate of his teammate's SA in a flight simulator game performed by eight dyads. The authors argued that the significant correlation would hold only with overlapping task responsibilities between teammates.

An interview with a firefighting subject matter expert (Messier, 2011) revealed that firefighting crews are divided into several sectors that are assigned different tasks such as rescue, ventilation, lobby, or fire attack, etc. Some sectors need to have a higher level of mutual SA than other sectors. For instance, the fire attack sector (responsible for fire suppression) presumably has more SA similarity with the ventilation sector (responsible for opening airways into a structure to assist with the fire extinguishment) than with the lobby sector (responsible for finding stairway/elevator access to the fire source) (also in the Ottawa Fire Services Strategies and Tactics Manual, 2010).

Moreover, aspects of SA that team members do not share are at least partially compatible. Martin and Flin (1997) assessed the SA of thirteen fire incident commanders (the highest-ranked leader in an operation) and crew officers (leader of a smaller crew of firefighters assigned to a sector). The authors coded all of the critical information necessary in a firefighting operation into several categories. In the end, they concluded that the commanders and officers reported information in all categories. However, frequencies of critical information from each category varied depending on whether the person was an incident commander or a crew officer. Thus, this pattern seems to suggest that it is more important for teammates with different roles to have complementary, rather than similar (that is nearly identical) SA, to build a collective common ground.

While the qualitative study by Martin and Flin (1997) was insightful in terms of the knowledge that it extracted from the mental work of the firefighting personnel, the authors did not perform a quantitative analysis to more concretely present their data. In addition, they also did not comment on the accuracy of the team SA as it was not enough for the team members to have shared or compatible SA, but also for their SA to be accurate. SA accuracy is very important because, when two people have incorrect SA or when only one of them has the correct

SA, they will not develop a true picture of the situation and this could lead the team to make faulty decisions with unfavourable consequences (Endlsey, Bolte, & Jones, 2003).

Therefore, team SA can be considered optimal when each individual has the SA that is needed by his or her assigned task in the team, when it has the proper degree of overlap or similarity according to the responsibilities and roles of the team members, and also when all the teammates involved accurately perceive, integrate, and project their situation-critical information. When the team SA is optimal, it is more likely to facilitate team performance, as discussed in the next section.

Team SA and Performance

Individual SA has been shown to predict individual performance, but is the same pattern also observed at the team level? Empirical research shows that team SA positively predicts team performance. Sonnenwald and Pierce (2000) found that information-sharing behaviours that increased TSA in the command and control military squad at the battalion level were crucial to the success of the mission. Particularly, they observed that the failure of one battalion subgroup to share awareness of the battlefield situation with another subgroup during a training exercise resulted in a major casualty. Similarly, Roth, Multer, and Laslear (2006) also found that strategies employed by railroad workers and train dispatchers to build, share, and maintain TSA were important in keeping a high safety standard in the train operation.

Entin and Entin (2000) recruited mid-career United States Navy officers to participate in their simulated tactical mission experiment (driving out an invading army) and measured their team SA and performance with a quality rating questionnaire. The researchers found that team SA significantly correlated with team performance in a positive direction. In the previously discussed study by Sulistyawati et al. (2009), sixteen military pilots played a flight simulation game in teams of two. One person was in charge of formulating the strategies and monitoring the progress of the operation and the other person played a wingman who executed the plans laid out in the strategy. The performance measure was team survivability in the game and the team SA was measured with SAGAT, a widely used SA assessment tool where the task is periodically paused in order to ask the participants about the characteristics of the current situation. Results showed that teams with a higher collective SA were more likely to survive attacks from the enemies, compared with teams with a lower level of SA and this difference was statistically significant.

Just as individual SA facilitates individual performance, team situational awareness is also predictive of the team performance. However, the relationship between SA and TSA with performance does not exist in isolation of other factors that can either facilitate or degrade the performance. One such factor is workload and it is discussed in the next section.

Situation Awareness and Workload

The SA that an individual or a team possesses can be hindered by other phenomena or properties of the human cognition. Endsley, Bolte, and Jones (2003) listed eight phenomena of human cognition named "SA demons" and one of these demons is workload. Workload can be defined as " (1) imposed task demands-difficulty, number, rate, or complexity of the demands on an operator; (2) the level of performance an operator is able to achieve; (3) mental and physical effort an operator exerts; and (4) an operator's subjective perception of the task difficulty/complexity"(Huey & Wickens 1993, p 54-55). According to Endsley et al. (2003), a higher level of workload will exhaust the limited cognitive processing resources of the human mind. This can be detrimental to the person's SA quality, and the higher the task's demand is, the more difficult it is for the operator to keep track of the information relevant to the three levels of

SA. For example, a team member who is preoccupied by a heavy workload probably finds it more difficult to communicate with a teammate to get an update on the current situation. A study previously discussed (Entin & Entin, 2000) also measured the subjective workload of participants and it was found to correlate negatively with the team SA, albeit in a marginally significant way. However, a deeper look into the literature showed that the relationship between workload and SA is not as straightforward as originally thought.

Endsley (1993) postulated that SA and workload are not significantly related to each other as constructs. To test this hypothesis, she collected data of subjective workload and SAGAT scores from six pilots performing a combat flight simulation task. She did not find any consistency in the relationship between the two measures, and only two of the six pilots had lower SA coupled with high workload. Vidulich (2000b) performed a meta-analysis of how various interface designs influenced the operators' SA as indicated by various measures of SA and other constructs related to SA, including mental workload. The idea was that, if SA and workload are negatively correlated, interface designs intended to improve SA should also reduce the subjective level of workload. While the revised designs did improve SA, they had no significant effect on the perceived workload. A follow-up on this study (Vidulich, 2000a) also found similar inconsistency revealed in the first study: the interface revision that enhanced SA did not always reduce mental workload. Therefore, the author concluded that lower SA did not necessarily equal high workload or vice versa.

Saner et al. (2009) attempted to test the hypothesis that lower perceived workload would be negatively correlated with better individual and shared team SA. The field study involved members of the US military performing five combat simulation scenarios of increasing task difficulties (each with a different objective). They measured the self-reported SA rating and SA accuracy of the personnel with regression analysis to see if the two measures were related. The results showed that the level of subjective workload did not significantly correlate with both individual and shared SA. Similarly, Ma (2012) found, in her forest firefighting simulation study, that teams' perceived workload levels were not significantly related to their performance and TSA. In contrast, Brandigampola (2011) found that participants' performance degraded and TSA scores were lower when the experimental condition imposed a higher workload.

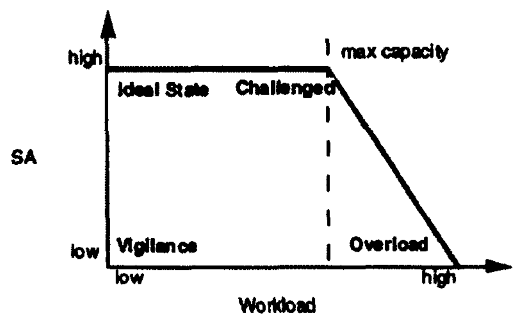


Figure 1. The relationship between SA and workload. Adapted from "Situation Awareness Information Dominance and Information Warfare," by Endsley, M., & Jones, W. M., 1997, *DTIC Document*, p. 30.

There are several explanations that have been offered to make sense of the unclear relationship between SA and workload. Endsley and Jones (1997) explained, as shown in Figure 1 above that, generally, SA and workload are independent of each other when the workload level is low or moderate, but as the workload level becomes too high, SA will decline because the increasing amount of information and task demands may leave little room for the operator's mental capacity to maintain SA. In some cases, operators have low SA and low workload because operators do not put much effort into the task. At other times, an optimally designed system interface facilitates SA without the operator having to work hard to maintain a high SA (Vidulich 2000a; 2000b). However, it is possible to have high SA in spite of high workload because an operator may switch to a more effective strategy to cope with the increasing workload and a higher level of workload can come from exerting more effort to increase SA (Endsley, 1993).

In summary, the relation between SA and workload is inconclusive because it is dependent on a myriad of contextual factors such as the system design and the individual's strategy to cope with the task demand. Moreover, an examination of SA and workload should also take into account the frequently unpredictable nature of the working environment, particularly when the change in workload level cannot be anticipated in advance.

Sudden Obstructions and Change of Workload

Firefighters work in a dynamic environment where the situation can change without notice and consequently the level of workload can change suddenly due to the occurrence of these unexpected events. For instance, the intensifying fire and heat in a structure can suddenly lead to an explosion that may necessitate a change of strategy by the fire commander, and the crew must act according to that change of plan. Since the workload shift, also known as the workload history effects, or workload transition, (Cox-Fuenzalida, Swickert, & Hittner, 2004), is a reality that emergency workers must cope with, it is relevant to explore this further.

Previous research has shown that workload shift, or sudden changes in workload level (increase or decrease) were often associated with decrement in performance (Cumming & Croft, 1973; Matthews, 1986; Cox-Fuenzalida, et al., 2004). Cox-Fuenzalida et al (2006) asked 149 undergraduate students to perform the Sternberg memory task to test the effect of workload history on performance. In the task, participants had to memorize a set of six letters and probe letters were presented afterwards. Participants were then asked to respond if the probe letters were parts of the original six letters. The independent variables were the workload shift condition they were assigned to: high to medium and low to medium conditions (researchers established the rate of presentation and the corresponding workload levels during the pilot study). Workload was induced by manipulating the presentation rate of the probe letters and this was measured by NASA-TLX, a widely-used subjective workload assessment tool. The researchers found, from their results, that the participants performed more poorly in both high to medium and low to medium conditions compared to the baseline conditions, where no workload change was induced. Moreover, participants in the high to medium condition (decreasing sudden workload shift) performed more poorly and they reported a higher level of workload compared to their counterparts in the low to medium condition. This implies that a sudden decrease in workload actually results in a larger performance decline than a sudden increase in workload.

One possible explanation for this interesting finding is that participants who previously started with high workload level exerted a high level of effort that they then retained after the workload level decreased (Matthews, 1986). Another explanation is that when participants perceived the high workload level, they were more likely to accept a higher level of errors, but because they did not expect that the workload amount would shift downward, that expectation of high error level persisted (Cumming & Croft, 1973). Goldberg and Stewart (1980) suggested that the initial high workload exhausted the short-term memory and fewer mental resources were available by the time the task demand was lowered. One limitation that was not addressed in the study by Cox-Fuenzalida (2006) was that the researchers did not experiment with medium to low and medium to high conditions to see if such conditions yield any significantly interesting results.

Cox-Fuenzalida (2007) followed up the 2006 study with a different laboratory task (Balkan Vigilance Task) where participants heard the audio presentation of a series of odd-even-odd trios of numbers and their task was to press a key when a signal was detected during the presentation of numbers. The author manipulated workload level by manipulating the rate of digit presentation (high to low or low to high) and performance was measured by total correct responses, errors, and reaction times. While there were no significant differences between the two groups in response times, both groups performed worse than in baseline conditions and the low-to-high group outperformed its high-to-low counterpart. However, in this study the author curiously did not utilize a medium level of workload as was done in her 2006 study.

A forest firefighting simulation study by Jobidon, Breton, Rousseau, and Tremblay (2006) showed that the effects of workload transition demonstrated in the laboratory, as reviewed thus far, also had an impact in the setting of applied research. The researchers asked participants to work in teams of two where they were either dependent (functional team) or independent (divisional team) of each other for the successful completion of a fire suppression task while having to put out fires that could start unexpectedly at any location in the simulation. While they saw some differences between the two team types, the main effect of the workload shift was significant and both teams performed worse after the occurrence of the unexpected fires versus prior to it. However, Jobidon et al. (2006) did not measure the subjective workload of their participants and this shortcoming was addressed by Morgan and Hancock (2011) in their driving simulator study.

Morgan and Hancock (2011) had 38 participants driving a car simulator with heads-up display navigation system that was programmed to fail at a certain point in the experiment and the subjective workload, as well as the drivers' reactions to the GPS failure were recorded. Consistent with the laboratory studies, they found that the subjective workload level post-navigation system failure was significantly higher compared with the pre-navigation system failure. Researchers observed that the participants had a higher percentage of braking actuation (drivers pushed the pedal much farther when they braked, which is equivalent to poorer vehicle control). However, they warned the readers about the dissociation between subjective workload and performance (Vidulich & Wickens, 1986; Yeh & Wickens, 1988) and called for a careful interpretation of the subjective workload and brake actuation data in their study.

It is evident that the literature consistently points to the negative effect of workload shift on performance and thus, the SA and performance of firefighters should be examined in the light of the unexpected challenges they encountered during their mission. Another topic of interest in this study is the impact of the spatial configuration of the fire incident sites, although it is not always necessarily unexpected.

The Architectural Legibility of Indoor Fire Incident Sites

Indoor firefighting requires fire emergency responders to enter an unfamiliar building where they navigate a space often under conditions of low visibility from smoke or inadequate illumination (Ramirez et al., 2009). Firefighters are equipped with the experience, training, and tools to operate in such environments better than non-firefighters. For instance, Dyrks et al. (2009) observed in their live action role-playing workshop that the firefighters in the exercise could answer navigational questions such as, "How big is this room?", "How many rooms did we already scan?", and "How do we find the way back?" more accurately than their laymen partners. Nevertheless, navigation under such hazardous conditions is always a source of risk (Fahy, 1977).

Ruppel et al. (2010) suggested that large buildings with convoluted, maze-like floor plans add even more way-finding difficulties and risks to firefighters. The lower architectural legibility demands more orientation work, which wastes precious minutes from the ultimate goals of saving lives and property. Research has indeed found that individuals' way-finding performance is largely influenced by the level of the structure's architectural legibility, which is defined as, "the degree to which a building facilitates the ability of users to find their way within it" (Weisman, 1981, p 189). More specifically, Kaplan and Kaplan (1982) suggested that a legible environment appears easily travelable with miniscule chance of getting lost, even as one roams deeper into the space.

The floor plan configuration is one way to operationalize the construct of legibility of an environment. One particular criterion is the adherence of the layout shape to Gestalt "goodness of form" characteristics such as symmetry, regularity, and continuity (Canter, 1974). Weisman (1981) took the layouts of 10 buildings at the University of Michigan and produced schematically simplified versions of the blueprints. The author then asked 20 raters to evaluate the drawings based on five criteria of personal preference, complexity, ease of description, memorability, and perceived ease of way-finding. The rating responses were subsequently dichotomized into high and low levels of those criteria (e.g., low/high complexity; low/high memorability, etc). A second part of the study asked 73 University of Michigan students (different from the 20 raters in the first part of the study) to respond to questionnaires that tapped into the familiarity, self-reported way-finding performance, and subjective comprehension of the buildings' spatial properties.

A comparison of the results between the two parts of the study showed that the higher the complexities of the blueprints, the more likely it was for students to report being disoriented in those buildings. More specifically, the perceived complexity of the blueprints accounted for 56% of the variance in the questionnaire data. There was also a marginally significant positive correlation between the ease of travel in the buildings from the blueprints, and self-reported way-finding performance. Interestingly, while the majority of the participants reported superior way-finding behaviours, a significant minority of the subjects reported disorientation, although they were at least familiar with the buildings. Further examination into familiarity surprisingly showed that it did not largely predict reported way-finding behaviours. Some issues with this study had to do with the dichotomization of the five blueprint characteristics' scores, absence of objective performance measures, and reliance on the subjective perception of the layout complexity.

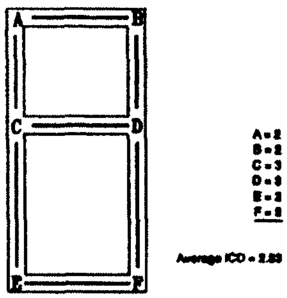


Figure 2. An example of ICD calculation. The diagram above is a simplified drawing of a floor plan/blueprint with six choice points (A to F). Choice point A is connected to 2 choice points (B and C) thus A = 2, choice point C is connected to 3 other choice points (A, D, and E), thus C = 3, and so on and so forth. 2 +2 +3+3 +2 +2 = 14/6 = 2.33. Adapted from "Evaluation of a Conceptual Model of Architectural Legibility,"by M. J. O'Neill, 1991, *Environment and Behavior, 23*, p. 266.

O'Neill (1991a) used the Inter Connection Density (ICD) index which is a measure of the density of choice point connections within an area, where a higher number indicates a higher complexity of the floor plan (please see Figure 2 for a sample calculation). ICD is a popular method in the field of spatial syntax, which is defined as, "a family of techniques of representing and analysing spatial layouts of all kinds" (Hillier, 1999, p.169). At its inception, space syntax research was intended to study the relationship between urban environmental structure and the resulting movement behaviours (Penn, 2003). Over time, its evolution has led space syntax methods to be applicable in predicting movement patterns within built environments as well. There is a general consensus in the literature that spatial syntax is effective in explaining, predicting, and quantifying the navigating behaviour of pedestrians and drivers (Peponis et al., 1989; Read, 1999; Penn, 2003). It has also been useful in the analysis of way-finding behaviour within indoor environments given its spatial complexity (Holscher & Brosamle, 2007; Li & Klippel, 2010). Holscher and Dalton (2005) compared ICD with several other syntax methods and found it to be the measure that accounted for the most variance in the participants' performance.

O'Neill (1991a) took the configuration sketches of three areas in the SUNY Buffalo library with different levels of legibility as quantified by their indices of topological (associated with connection between different places rather than metrical elements of distance and direction) complexity using the mean ICD. Participants were not familiar with the library and the training session of the study involved having them view sequential photographs (self-paced) of a guide walking on each floor through relevant choice points, from a starting point to a destination, thus navigating the environment without physically entering the library. They were then asked to sketch maps of the floor plan and mark the locations presented on the photographs on their sketch maps to evaluate the accuracy of their cognitive maps. Subsequently, they were told to perform actual way-finding tasks in the library that were assessed using the time taken to complete the task, frequency of backtracking behaviour, and number of wrong turns.

The results revealed that participants had significantly less accurate sketch map markings and worse way-finding performance (more turning errors, more time, and more backtrackings) with floors having higher mean ICD compared with floors with lower mean ICD, even after taking into account their individual sketch map accuracy. Interestingly enough, it did not take a lot of differences in the ICD values of the three library settings in this study (the ICD for library setting 1= 2.40, ICD of library setting 2 = 2.45, and ICD of library setting 3 = 2.54) for the participants to have significantly different way-finding performances among the three library locations. Through a path analysis method, the author concluded that the topological complexity of a floor plan affected its legibility, which in turn predicted way-finding performance through the mediating effect of the environment's cognitive representation. This study was thorough and had the advantage of observable assessments, the usage of mean instead of the sum of ICD values (without averaging them), and a testable causal model deserving further investigation.

The follow-up for the study discussed above included a combination of subjective and objective judgements of the floor plan complexity while also examining the moderating effect of signage on way-finding performance. O'Neill (1991b) took twenty five simplified floor plan schematics derived from buildings at the University of Wisconsin-Milwaukee and calculated their ICD values after having participants rate the diagrams in terms of their simplicity and legibility (level of ease in understanding the floor plan). The author took a sample of 5 floor plans of different ICD values out of the 25 pictures and discovered that the participants' subjective judgment of the complexity matched the ICD values for all except for one symmetrical floor plan. The symmetrical floor plan had the highest ICD, but it was perceived as the third simplest design out of the five plans. The researcher recruited another set of participants to perform way-finding tasks on the five buildings sampled earlier and scored the navigation performance based on rate of travel, wrong turn error, backtracking behaviour, and stopping & looking behaviour.

Analysis of data on the four aspects of the dependent variable showed that, similar to the author's earlier study, the way-finding performance generally declined with increasing ICD values of the floor plans, although significant increase was not always observed. One particular exception was that participants in the building with the symmetrical configuration had the highest rate of travel (best on this aspect of way-finding) in spite of the fact it had the highest ICD. This may suggest that ICD should be evaluated with other properties of the floor plan, such as the symmetry in that particular study. Signage was also shown to compensate for the legibility of layout configuration with the exception for wrong turn error, where the complexity variable appeared to prevail over the presence of relevant signs in the area. The most valuable lesson learned from this follow-up study was the combination of the objective and perceived floor plan complexity judgments, but O'Neill (1991b) curiously did not explain why he chose these particular five designs out of the twenty-five that he originally had in his inventory (with the exception of the symmetrical design).

Research in other domains where performance is dependent on the processing of spatial information provides some empirical support that those spatial elements also contribute to the SA of the operators. Durso and Sethumadhavan (2008) found, in two studies in the air traffic control and aviation fields, that spatial working memory is one of the several constituents of SA. Wickens (2002) emphasized the importance of the perception, integration, and projection of critical spatial cues (altitude, orientation, and flight path position, to name a few) for the safe travel of the airplane. In agreement with Wickens' (2002) point, Bolton and Bass (2009) found that their pilot participants had a significantly more accurate judgment of flight terrain points when they used the cockpit display, which they subjectively perceived to enhance their spatial awareness, although they were ambiguous on how the displays objectively supported the pilots' SA. In the driving literature, Gugerty (1997) found, through his driving simulation study, that, with higher SA (operationalized by their recall of cars' locations in the surrounding traffic), drivers detected more traffic hazards and avoided them accordingly.

Based on the brief review of architectural legibility literature, there is some strong evidence that higher complexity of floor plan configuration can have a negative effect on way-finding performance. The spatially confusing structure of a building may pose a serious challenge to the firefighters in their effort to locate fire and victims in already less-than-ideal conditions of a building on fire. Therefore, it is possible for the poor architectural legibility of a building to degrade the SA of the firefighters looking to find victims and fire.

If a building's poor legibility impedes the firefighters' ability to spatially process their surroundings, then complex configuration may negatively affect their SA and performance as well. Therefore, it was important to study how that additional challenge of building complexity influences the situational awareness and performance of firefighting crews that must also regularly cope with insufficient information about the people and properties they are fighting to save (Jiang et al. 2004).

The Importance of Information Completeness

Having the right information at the right time is essential to build and maintain all three levels of SA. Endsley and Jones (1997) argued that information status mediates the relationship between SA and performance. A lack of background information regarding the fire incident can potentially have a negative effect on SA and performance. This is because, in order to have situation awareness, one must first assess the situation (Endsley, 1995) by gathering information about that situation (Proulx, 1993). Not surprisingly, the less information an individual possesses, the larger is his/her uncertainty about the situation.

When information is lacking, teams can choose to obtain more information, which can be time-consuming and might potentially jeopardize the mission. Otherwise, they can improvise with the current and possibly incomplete level of information. Unfortunately, the execution of actions or the decision making with insufficient understanding of the situation can lead to undesirable performance (Canter, 1980).

According to Endlsey, Bolste, and Jones (2003), uncertainty of information can affect SA negatively in each of its three levels. At the level of perception (level 1), SA is vulnerable to:

1. Missing Information: a very common and significant source of uncertainty (McCloskey, 1996 as cited in Endsley, Bolste, and Jones, 2003, p. 117).
2. Unreliable Data: data in various domains and fields are mostly gathered by sensors, none of which are perfectly reliable. As a result, the credibility and reliability of the data can depend on the quality of the sensors.
3. Incongruent/Conflicting Data: all kinds of information with varying levels of accuracy on the same phenomenon compete for the operator's decision. Deciding which information is correct and which is incorrect can be time-consuming and may hinder performance.
4. Untimeliness of Data: are the required data available on a regular basis or at the moment they are needed?
5. Ambiguous or Noisy Data: Are we sure that we have the information we want, or are they irrelevant, distracting "noises"?

When uncertainty affects level 2 of SA, the individuals are coping with what is called the comprehension uncertainty. Obviously, contaminated level 1 data can taint their proper interpretation. At this stage, even if each of the level 1 pieces of information gathered is uncompromised, there can still be some uncertainty when interpreting the meaning of the aggregated data. For instance, a doctor can be 80% sure of the certainty of diagnosis, given the results of the various medical tests on a patient (Endsley et al., 2003). Projection uncertainty (level 3) can result from uncertainty in the underlying level 1 and 2 information, but the operators' competence in projecting the future states of the system also matter. All systems have some degree of projection uncertainty attached to them.

Much research has been conducted on the effect of poor information quality on performance and SA due to communication breakdown. The Joint Commission for Hospital Accreditation attributed 70% of patient harm to communication failure with fatalities in 75% of these instances (Leonard et al., 2004). Parush et al. (2011) qualitatively identified that 63% of TSA-related communication in the operating room (OR) is susceptible to information loss due to open-loop communication, delayed response to communication, and vague identification of the messages' recipients. Wauben et al. (2011) discovered that poor information and SA can be traced to a discrepancy in the perception of adequacy of SA and communication among different OR team members. Particularly, surgeons tend to believe that communication and SA in the OR nowadays is adequate, while nurses perceive them to be inadequate. Various training programs designed to improve communication and to provide structure to the information distribution are associated with significant improvement in patient safety (Leonard et al., 2004; Reader et al., 2007). This improvement is especially robust when the training program is intensive (McCulloch et al., 2011)

Another motivation for this study is how firefighters perform their duty without knowing all the information necessary for the success of the team's mission (Jiang et al., 2004; Dyrks et al., 2009). While communication is an important part of information transmission, another focus of this study is on the completeness of information provided prior to the mission. In this context, the effect of incomplete information on team SA was empirically investigated in this study. As a higher level of situation awareness depends on the quality of content of its lower level counterpart, missing information (level 1 uncertainty issue) was the type of uncertainty studied. As previously mentioned, missing information is a very common and significant problem in this subject and thus, its relevance in this study is warranted.

Summary

The high-risk nature of firefighting makes it important to examine factors that both facilitate and degrade the performance of the firefighters, particularly with respect to their teamwork. In this study, the interests lie in the variables that are likely to influence the relationship between TSA and team performance. Although previous research has shown that spatial awareness becomes an integral component of SA when team performance relies on the processing of spatial cues, just like in the firefighting domain, there has been virtually no study looking into how external factors, inherent to the surrounding environment, particularly its architectural legibility, can affect SA. In addition, firefighters must often work under the less-than-ideal conditions of not having enough information while entering a burning structure. The inconsistent level of information completeness or deficiency can also have an impact on performance and SA. Finally, the unpredictability in firefighting situations implies that the firefighter crew's workload level can change at any given moment without any prior notice, and research suggests that this workload shift degrades performance and possibly SA. This empirical study was conducted to analyze how these three variables can affect the link between TSA and performance.

Goals and Objectives

The goal of this thesis is to contribute to firefighting effectiveness and safety by understanding the effects of architectural legibility of an environment and the availability of critical information on team situation awareness and performance. These effects were examined as a function of unexpected challenges typically occurring during firefighting situations.

The objectives of this study were:

1. To examine how different levels of architectural legibility influence performance and TSA;
2. To study how information completeness influences performance and TSA;
3. To analyze how these two factors exert an effect on performance and TSA when the situation changes unexpectedly.

Research Questions:

1. Does the level of a building's architectural legibility influence TSA and performance?
2. How will information completeness influence TSA and performance?
3. How do sudden changes in the situation influence TSA when combined with the effect of architectural legibility and information status?

Hypotheses:

1. Floor plans with lower architectural legibility degrade TSA and team performance more than simpler floor plans
2. Lack of task-critical information will degrade TSA and team performance
3. A workload increase associated with a sudden change during task execution will degrade TSA further when there is a low level of architectural legibility and when there is not enough information.

Methods

Participants

A total of 53 teams (106 individuals) originally took part in the study through Carleton University's SONA system. All participants received extra course credits towards a psychology course in exchange for their involvement in this study. After the data were cleaned, 21 teams (42 individuals) were picked for analysis. Teams that were not analyzed were discarded due to various reasons including software crashes in the middle of the session, teams' failure to encounter obstruction, teams seeing the obstruction before being given the first SAGAT probe, and teams encountering the obstruction too late after the third SAGAT probe. Minimum age was 18 and the oldest participant was 39 years old. The average age of the participants was 21.5. 23 out of the 42 individuals (54.76%) were females and 19 out of 42 (45.24%) were males.

Tasks and Design

Experimental Tasks. In this study, two participants played the roles of two firefighters of equal ranks in a given crew (team) responsible for locating all fires and victims in a building. There were four scenarios, each lasting ten minutes, played in a desktop virtual reality simulation. Two scenarios took place in a burning four-storey apartment building and the other two in a seven-storey burning office building. The teams searched only three floors in each of the scenarios. The two structures were chosen because one had a complex layout (office building), while the other had a simpler layout (apartment building).

Study Design. The study followed a randomized block, repeated measures, 2 X 2 X 2 design with counterbalanced order of scenario presentation (note: counterbalancing was only done with regards to the architectural legibility and information status variables). Possible order effects due to scenario presentation sequences were analyzed.

1. The first within-group independent variable was the level of architectural legibility. In one condition, teams worked in a virtual apartment building with a higher level of architectural legibility based on its low ICD value. All the units in the apartment building have identical floor plans but with different furniture arrangements and wall colours. In the second condition, teams worked in a virtual office building with a lower level of architectural legibility based on its higher ICD value. The office building was a seven-storey building with identical floor plans and furniture arrangement (except for the lobby and the basement garage, both of which were not used in the study) but different wall colours. The building type was the blocking factor in the randomized block design. Please see Appendix A for the ICD calculations of the two floor plans.
2. The second within-group independent variable was the amount of critical information given to the participants prior to performing their tasks. Complete information included the number, distribution, and locations of the fire and victims in the building. Incomplete information included the knowledge the fires and victims' presence, but their distribution, number, and location were withheld.
3. The third within-subject variable was the obstruction sequence (pre- and post-obstruction). Performance prior to and after obstruction encounter was analyzed along with the other two independent variables.

Table 1

Four Experimental Scenarios (Pre- and Post-Obstruction)

	High Architectural Legibility (Apartment)	Low Architectural Legibility(Office)
Information Status: Complete		
Information Status: Incomplete		

Experimental Scenarios. A total of six scenarios were developed consisting of two training scenarios and four experimental scenarios. In each scenario participants were asked to enter a burning building and locate all victims and fires within ten minutes (timed with a stopwatch by the experimenter). Fire obstructions were introduced in each of the scenarios in order to simulate the experience of unexpected events and induce workload shift. Specifically, the fire obstructions were placed in such a way to force the participants to find ways around them. There were eight orders of the four experimental scenarios' presentation (see Appendix H for the counterbalanced orders of the experimental conditions)

In the two apartment building scenarios, a fire obstruction was placed on the only stairway connecting the first and second apartment units, thus forcing the team to find alternative ways to get to the rest of the units. In the two office building scenarios, two fire obstructions were placed within the floors of the office building. The reason the office building had two fire obstructions is because each of the office floors has six rooms with two doors each. Consequently, the placement of two rather than one fire obstruction is necessary in order to effectively block the paths of participants while still giving them a way to resolve the problem.

The weather settings of all experimental scenarios was set to 100% cloud coverage with the sun position at 6 pm. All four apartment units on fire in the two high architectural legibility conditions were filled with smoke. The office floors on fire were only partially filled with smoke due to memory limitation of the software. In addition, participants were asked to have their avatars wore breathing masks, thus further obscuring the field of view. All of these measures were intended to simulate poor visibility which is a very common problem faced by real firefighters. The pilot study indicated that these settings still allowed participants to see the victims and the fires although they were working in poor visibility. For more details on the scenarios, please see Appendix B.

Apparatus

Three-dimensional virtual reality (first-person view) training software, XVR (by E-semble), was used to implement the scenarios and for participants to perform them. XVR was designed to train professional workers in the safety and security domains (e.g., police, paramedics, and firefighters) by simulating high-risk incidents (e.g., fire incidents, plane crashes, car accidents, chasing fugitives in a crowd). The goal of the product is to let these professionals practice and hone their teamwork and decision making skills in a safe virtual environment. For the purpose of this study, the software was set up to run firefighting scenarios in a residential urban environment. The virtual environment of XVR allows the experimenter to place items such as fires, victims, smoke, ladders, emergency vehicles, in the environment, and to control the visibility of the environment by changing the weather parameters (sun position, rain, snow, lightning, and fog).

The XVR simulation was installed on three locally networked PCs, one for the experimenter and a computer for each of the two participants. All three computers had the Windows 7 operating system installed, with the instructor's monitor having a 1440 X 900 pixels resolution and the two student monitors having a 1920 X 1080 pixels resolution. Participants experienced first-person viewpoints on their respective monitors while the experimenter could also view the activities of the participants from a bird's eye view.

XVR allows participants to open/close doors and get in/out of an emergency vehicle. Participants' avatars could also walk through the fire without getting burnt, but the study instructions specified that they could not cross it (i.e., to avoid fire as one would do in real life).

Some drawbacks of the program include the inability for the fires to spread, as well as the inability for fire suppression and victim extractions. Due to these limitations, the experimental tasks were limited to locating the fire and the victims.

The activities of the participants were captured from the bird's eye view by using the software Camtasia version 4 developed by TechSmith. (Please see Appendix C for a picture of the objective bird's eye view of the participants' avatars). A video camera was also used to capture both participants' computer screens in addition to their communication and activities as a team. The video camera was positioned to shoot the participants from behind looking over their shoulders and not capture their faces.

A demographic questionnaire covered participants' personal information that could influence the results of the study such as age, sex, familiarity with the teammate, first language, English fluency, and experience using computers/playing video games. The participants' names were not recorded in the demographic questionnaires (see Appendix D). However, the demographic questionnaires were coded by the times and dates the experiments took place to link them with other data from this experiment.

The training handout was on paper, with a PowerPoint format with 2 slides per page. The handout taught the participants how to perform certain navigational manoeuvres in the XVR virtual environment (e.g., walking backward, forward, kneeling, climbing ladders, going up and down the staircase, etc.) and what to do when they found a fire or a victim.

SA was measured with true/false statements following the SAGAT (Situation Awareness Global Assessment Technique) measurement method. The two participants were given the same question each time the questionnaire was delivered (see Procedure below). Please see Appendix E for the format of the true-false SA and workload probes, and Appendix F for the full list of the statements. Finally, a workload rating scale was used to rate perceived personal workload and the perceived workload of their teammate. The workload rating was on a scale of 0 (no workload perceived) to 100 (extremely high workload) with an increment of 10.

Procedure

Upon arrival, participants were asked to read and sign the informed consent form before filling in the demographic questionnaire. The two participants sat next to each other with a divider between them so they couldn't see each other's monitors and had to rely on communications to complete the tasks (see Appendix G for a picture of the physical layout of the experimental setting).

Using the training handouts, both participants were trained in using the joystick to operate their avatars. Participants were then instructed to drive their cars towards either the apartment or the office building (depending on what order of counterbalancing the team got). They were shown how to exit the car and how to practice using the joystick to move around the building (walking forward/backward, turning left/right, tilting head up/down/left/right, moving side-to-side, and kneeling down) and control the speed of their movements. Participants were also verbally guided by the experimenter.

Following the basic practice, participants practiced how to open and close the doors, walk up and down the stairs within the building, and climb up and down the ladder which rested against a balcony of the apartment building. Note that ladders were not be used with the office building because none of the windows of the office building could be opened and all available ladders were too short for its rooftop.

Given the blocking of the experimental conditions, participants could either start working with two apartment scenarios before two office scenarios or vice versa. The training was given according to the respective scenario. There were two versions of the training instructions (hence the two training sessions-see Appendices I and J), and only one per experimental session was used, depending on the counterbalanced order of scenarios in that session.

Following the training session, teams ran the two experimental scenarios relevant to the building with which they started. Prior to entering the scenarios, the experimenter provided them with the details of the mission including critical information regarding the fire and victims (depending on the information completeness condition) and the plan of the mission for each scenario that participants must strictly follow. If participants found a fire or a victim, they were required to make their avatars jump twice by pressing the keyboard's spacebar twice to indicate to the experimenters (who views the avatars' movements) that they had noticed the fire or the victim and to tell their teammates. As XVR did not let the participants extinguish the fire and save the victims, they resumed their search mission immediately right after they had found fires/victims. Participants were encouraged to split up once they were inside the same apartment unit or on the same office floor to expedite the search, although they could not leave behind their partners alone in a unit or on an office floor. However, whenever they found either a victim or a fire, they would need to communicate their discoveries to their teammates. If they thought that the victim or the fire they found had already been discovered by their teammate, they also needed to express that to their teammate.

Each scenario lasted 10 minutes and the experimenter used a stopwatch to keep track of the time. To increase overall scenario workload, the experimenter informed the participants every 2 minutes the remaining time left. In order to prevent cybersickness, or motion sickness-like symptoms reported in the virtual reality experience (LaViola, 2000), participants were allowed to have a short break at the intermissions between two consecutive scenarios and to have a snack or beverage should they bring food and drinks with them. The experimenter also provided the participants with water and snacks (crackers) if they had not brought food or beverages.

The experimenter paused the simulation three times: after three, six, and nine minutes from the beginning of each 10-minute scenario. When the simulation was paused, participants turned off their monitors, flipped over their mission plan sheet that informs them of general search strategy and information about the victims and fires (they could refer to the sheet throughout the scenario), and temporarily halted all communications with each other. They then responded to the SA and workload probes on a single sheet of paper. The SAGAT responses were scored as soon as the participants returned the probe sheets to the experimenter.

At the end of all experimental scenarios, there was a summative feedback questionnaire (see Appendix L). The questionnaire assessed subjective perception of the difficulty level of the tasks, how challenging the virtual environments were, the clarity of the instructions in the mission plans, the clarity of the training instructions, how difficult it was to use the joystick, and if they experienced any symptoms of cyber-sickness.

Measures

Teamwork Performance Measures. The experimenter tallied how many victims and fires the participants located and if they managed to overcome the unanticipated fire obstructions. Performance was assessed by calculating the percentages of victims and fires found in total and per floor (effectiveness measures). Efficiency measures were the mean rate of victims' and fires' discovery per floor, the mean time spent pre-obstruction/post-obstruction, and the mean time spent per floor.

The rate for finding victims and fires per floor was computed by dividing the time spent on a floor by the number of victims and fires found on that floor. This value was then averaged across the number of floors the teams managed to search until the end of the ten-minute time limit. The time was measured starting from when teams arrived on the floor until they had found the last victim and fire on each floor. The mean times spent pre- and post-obstruction were calculated by measuring how long, on average, each team spent searching prior to and after an obstruction encounter. The mean time spent per floor was assessed by measuring the time teams spent on each floor starting from the moment they arrived at the staircase until the time they were at the staircase to go to the next floor. For each scenario, the time was averaged across the number of floors where there were fires and victims that the teams could reach. All of the times were measured in seconds.

All of the efficiency and effectiveness measures were analyzed taking into account the obstruction sequence, architectural legibility, and information status in three-way 2 X 2 X 2 repeated measures ANOVA.

Team SA Measures. SAGAT (Situation Awareness Global Assessment Technique) was employed to measure the teams' SA responses, a commonly used assessment tool in SA research (Endsley et al., 1998). This method was developed by Endsley (1995) to evaluate SA by asking operators about their knowledge of the current state of the environment and comparing it to its actual state. Therefore, it is intended to be an objective and unbiased measure of all three SA levels, rather than inferring SA from the operators' performance and behaviours (Stanton et al., 2005). SAGAT works best with a simulation task because in this setting, the activity can be temporarily paused when the questions are administered. The confound of memory decay was avoided because the questions were asked concurrently during the task execution rather than after.

One immediately obvious drawback was the disruptiveness of the pauses, because that could possibly distract the responders (Pew, 1995). However, Endsley (1995) found no significant effect of freezes up to 5 to 6 minutes long. Stanton et al. (2005) also recommended that two successive pauses should be placed more than one minute apart and that the first one should not occur within the first 3 to 5 minutes. As many as three freezes in fifteen minutes of task also did not decrease the performance significantly (Endsley, 1995).

SA performance as a function of architectural legibility, information status, and obstruction timing points (before and after) for all the scenarios was analyzed with a 2 X 2 X 2 three-way ANOVA. The analysis of SA on the 2 levels of obstruction timing points revealed how workload influences SA.

Workload Measures. To measure the construct of workload, two workload rating scales were attached to each SA probe. Both scales asked participants to rate their current level of perceived workload and estimate the partner's perceived workload from a scale of 0 (no workload perceived) to 100 (extremely high workload). A three-way repeated measures 2 X 2 X 2 ANOVA was conducted to analyze the impact of the obstructions, architectural legibility, and information status on the workload ratings.

Results

The results of the analyses are divided into the three major categories of performance, situation awareness, and workload. The performance section is further organized by effectiveness and efficiency aspects. Fire search-related performance data is reported first, followed by victim search-related data. All of the measures were analyzed with a 2 x 2 x 2 (Architectural legibility [high/apartment, low/office] x Information Status [incomplete, complete] x Obstruction [pre, post]) repeated measures ANOVA. For all analyses, whenever there were significant two-way and three-way interactions, the focus is on the interaction with the larger effect size.

The fifty-three dyads initially recruited had to meet two inclusion criteria in order to be included in the analysis. First, data of teams that experienced technical difficulties during the experimental sessions were discarded as software would at times crash during the study (8 teams). Second, teams that encountered the obstruction prior to the administrations of the first (6 teams) or after the third SA/workload probes (8 teams) were also not used because the effects of the independent variables could not have been possibly measured pre- and post-obstructions. Two teams encountered obstructions prior to being administered the first probe and after given the third probe on two different scenarios (e.g., one team encountered obstruction before the first probe in the apartment-complete condition and after given the third probe in the office-complete condition).

Performance

Effectiveness of Overall Fire Search. The total percentage of fires found and the mean percentage of fires found per floor were calculated for this particular measure of team performance. Participants found significantly more fires when given incomplete (M = 74.41, SE = 2.50) rather than complete information (M = 67.46, SE = 2.90), $F(1, 20) = 4.93$, $p < .05$, $\eta^2 = .20$, and before (M = 89.88, SE = 2.22) compared to after the obstruction encounter (M = 51.98, SE = 4. 06), $F(1, 20) = 61.40$, $p < .001$, $\eta^2 = .75$. No main effect was observed for the architectural legibility factor.

The analysis also revealed significant two-way interactions where the obstruction encounter sequence differed depending on the architectural legibility $F(1, 20) = 43.58$, $p < .001$, $\eta^2 = .69$, and the information status, $F(1, 20) = 12.05$, $p < .01$, $\eta^2 = .38$. Figure 3 illustrates that the pre-post difference in the low-legibility/office condition was much smaller than in the high-legibility/apartment condition. Under complete information, fewer fires were found after the obstruction encounter, but the difference in fire percentage was much less pronounced with incomplete information (Figure 4).

There was also a significant three-way interaction involving all the examined variables, $F(1, 20) = 6.54, p < .05, \eta^2 = .25$. Here, there was virtually no pre-post difference in the incomplete/low legibility condition, while in the other three conditions, participants found many fewer fires post-obstruction (Figure 5). Given the smaller effect size of the three-way interaction, only the significant two-way interaction will be discussed further.

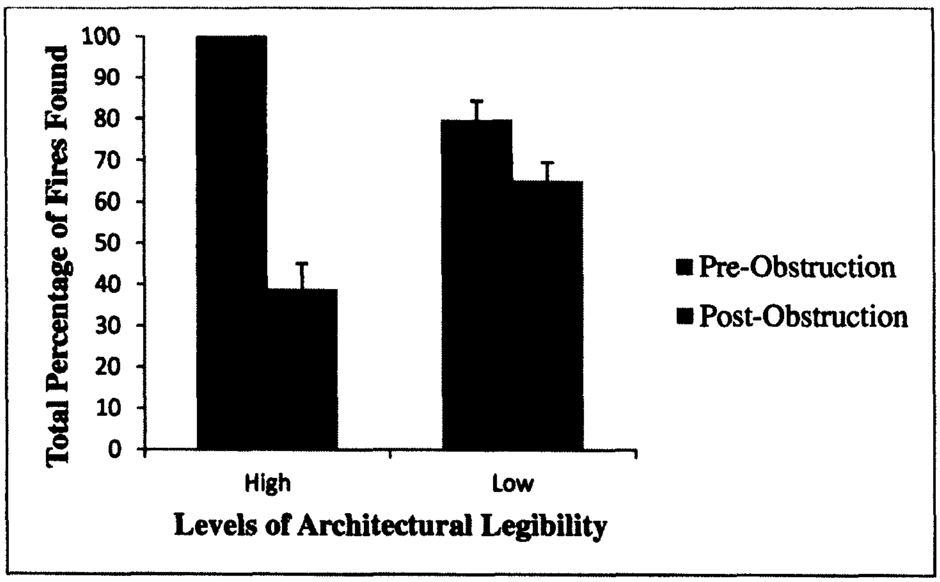


Figure 3. The interaction between architectural legibility and obstruction effect on overall percentage of fires found. Error bars represent standard error.

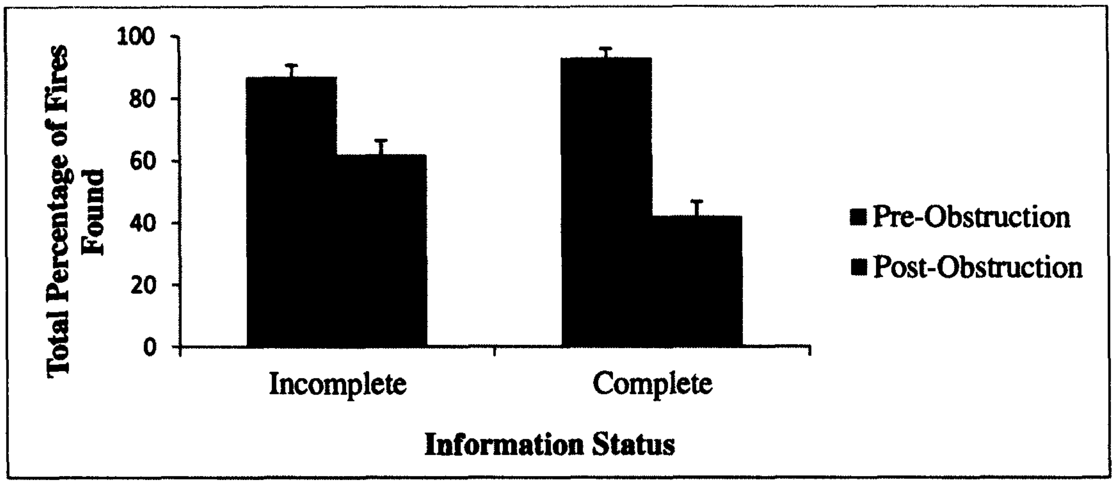


Figure 4. Two-way interaction between information status and obstruction effect on total percentage of fires found. Error bars represent standard error.

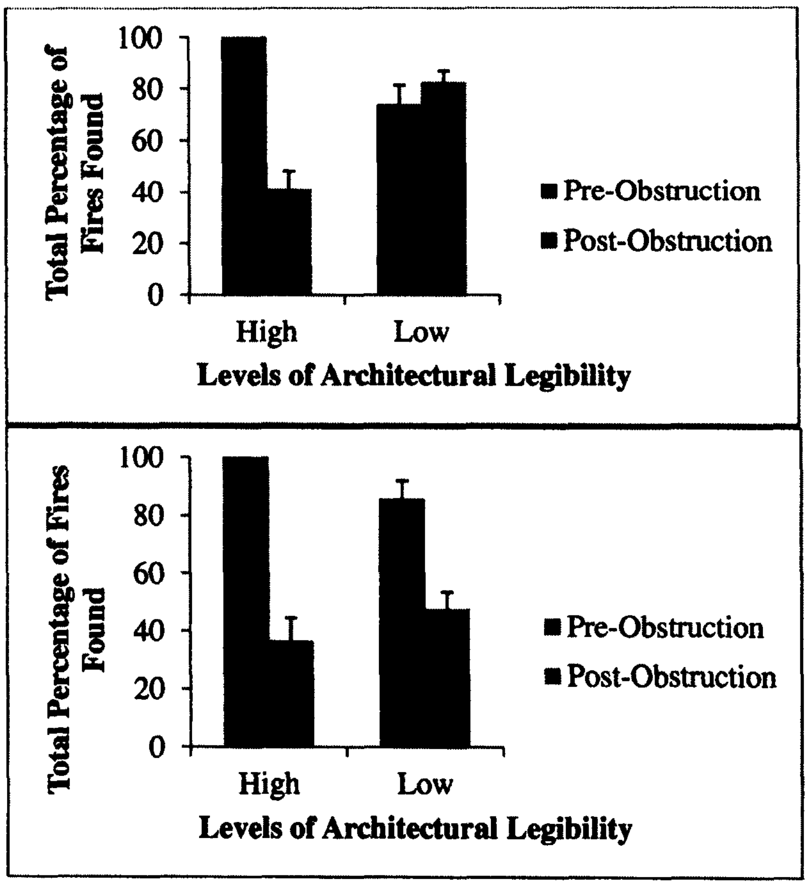


Figure 5. Three-way interaction between architectural legibility, information status, and obstruction effect on percentage of fires found, given incomplete (top) and complete information (bottom). Error bars represent standard error.

Effectiveness of Fire Search per Floor. Mean percentage of fires found per floor were calculated in addition to overall percentage from all floors searched. The only significant main effect was the lower mean percentage found post-obstruction (M = 65.63, SE = 4.97) compared to pre-obstruction (M =91.37, SE = 2.05), $F(1,20) = 27.20$, $p <.001$, $\eta^2 = .58$. The obstruction sequence variable interacted significantly with architectural legibility, where participants discovered far fewer fires post-obstruction in the apartment building, $F(1,20) = 12.05$, $p < .01$, $\eta^2 = .38$, than in the office building (Figure 6). Another significant interaction involving obstruction sequence and information status revealed that the gap between average pre and post-obstruction findings was larger when given complete information, $F(1,20) = 12.56$, $p < .01$, $\eta^2 = .39$ (Figure 7). No significant three-way interaction was observed.

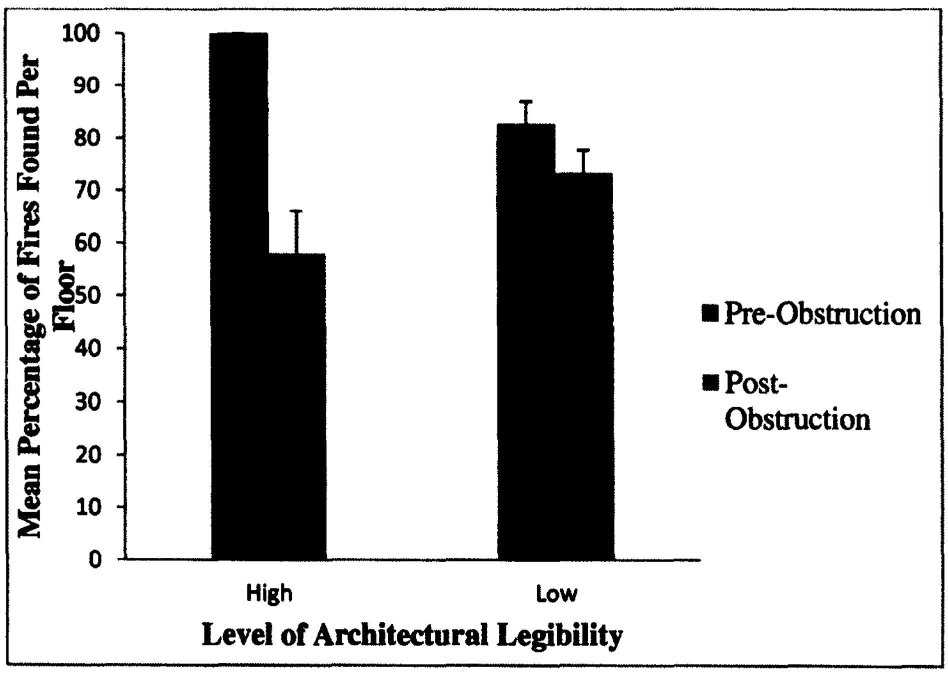


Figure 6. Interaction between levels of architectural legibility and obstruction effect on percentage of fires found. Error bars represent standard error.

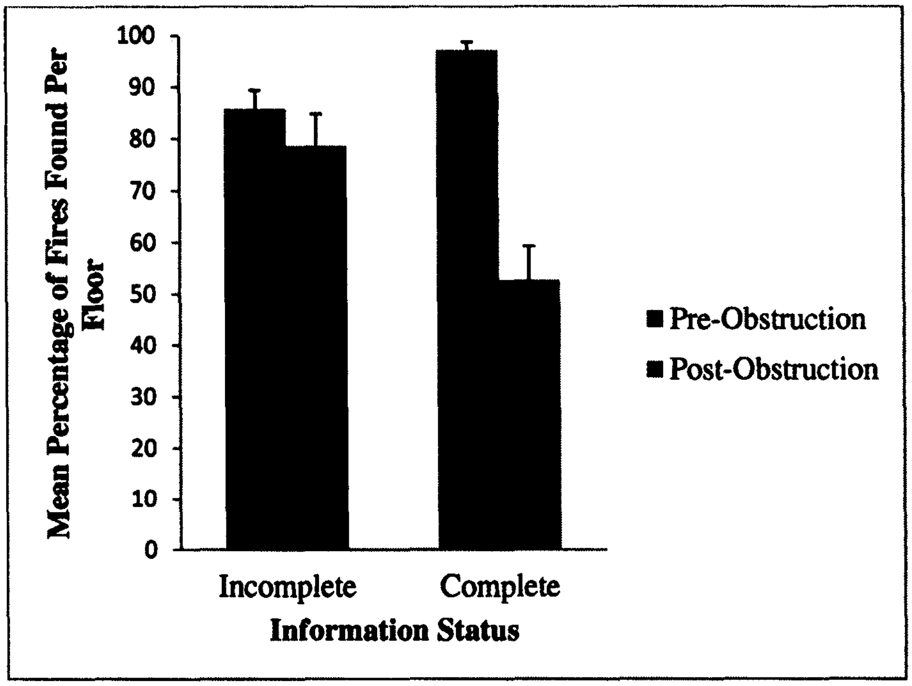


Figure 7. Interaction between information status and obstruction sequence on mean percentage of fires found per floor. Error bars represent standard errors.

Effectiveness of Overall Victim Search. Analysis showed the main effects of architectural legibility, $F(1, 20) = 6.80, p < .05, \eta^2 = .25$., and obstruction sequence, $F(1, 20) = 7.47, p < .05, \eta^2 = .27$. Performance was significantly better in the office/low-legibility building ($M = 41.67$, $SE = 3.49$), compared to the apartment/high-legibility building ($M = 28.97$, $SE = 4.71$) and worse post-obstruction ($M = 27.48$, $SE = 4.08$) than pre-obstruction ($M = 43.16$, $SE = 4.72$). The information status variable had a marginally significant effect on the dependent variable, $F(1, 20) = 4.09, p = .06, \eta^2 = .17$ with larger victim percentage in complete ($M = 39.98$, $SE = 3.49$) rather than incomplete information ($M = 30.66$, $SE = 4.58$).

The obstruction sequence interacted significantly with the architectural legibility variable, $F(1, 20) = 5.04$, $p < .05$, $\eta 2 = .20$, and the information status variable, $F(1, 20) = 11.65, p < .01, \eta^2 = .37$. Figure 8 exhibits the two-way interaction between architectural legibility and obstruction sequence where more victims pre-obstruction in the office-low legibility setting were found compared to apartment-high legibility building pre-obstruction. Furthermore, the pre-post difference in this interaction is only significant in the office building, with drastic discrepancy between the two sequences. Between information status and obstruction sequence, performance in the pre-obstruction and complete information condition was the most different (better) compared to the other three conditions (Figure 9).

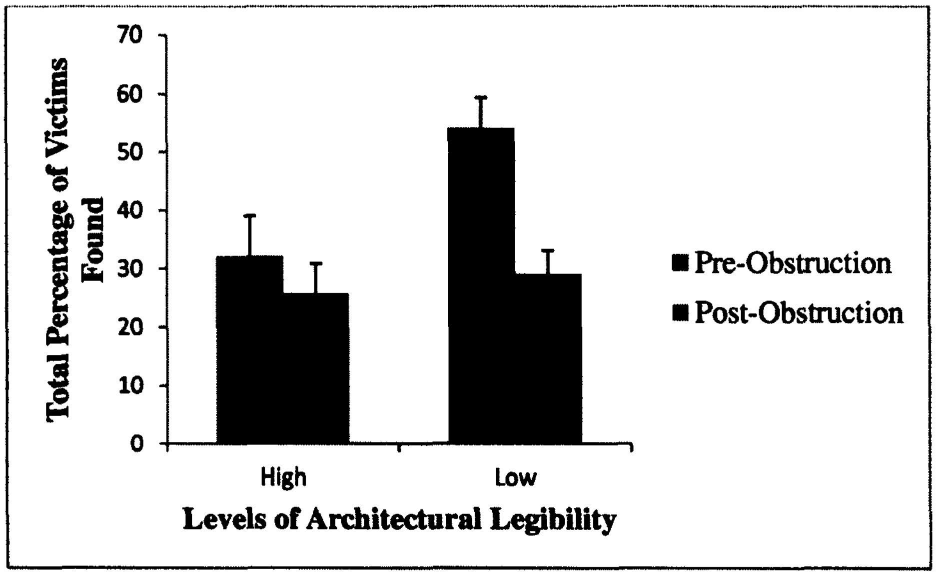


Figure 8. Interaction between levels of architectural legibility and obstruction sequence on total percentage of victims found. Error bars represent standard error.

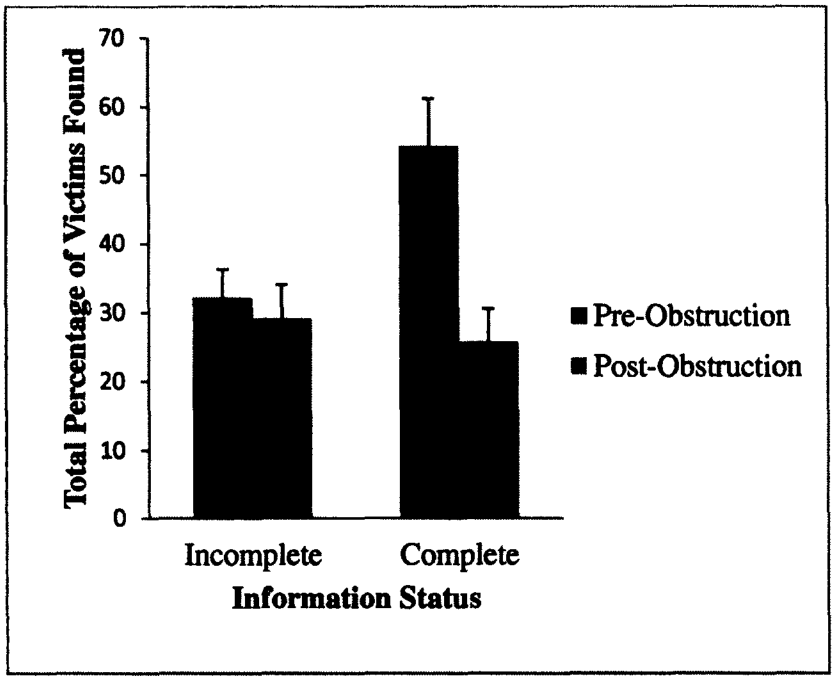


Figure 9. Interaction between information status and obstruction sequence on total percentage of victims found. Error bars represent standard error.

Effectiveness of Victim Search Per Floor. The main effect of architectural legibility was significant, $F(1, 20) = 6.19, p < .05, \eta^2 = .24$, with more victims found on average per floor in the low-legibility/office building ($M = 44.64$, $SE = 4.14$) than the high legibility/apartment building ($M = 32.71$, $SE = 4.64$). The main effects of information status and obstruction sequence were non-significant.

Information status and obstruction sequence showed a disordinal interaction pattern, $F(1, 20) = 19.16, p < .001, \eta^2 = .49$. Participants found more victims pre-obstruction with complete information compared to pre-obstruction with incomplete information (Figure 10). Moreover, the pre-post difference in the complete information condition is also significantly larger than the difference in the incomplete condition. No other interaction effects were observed.

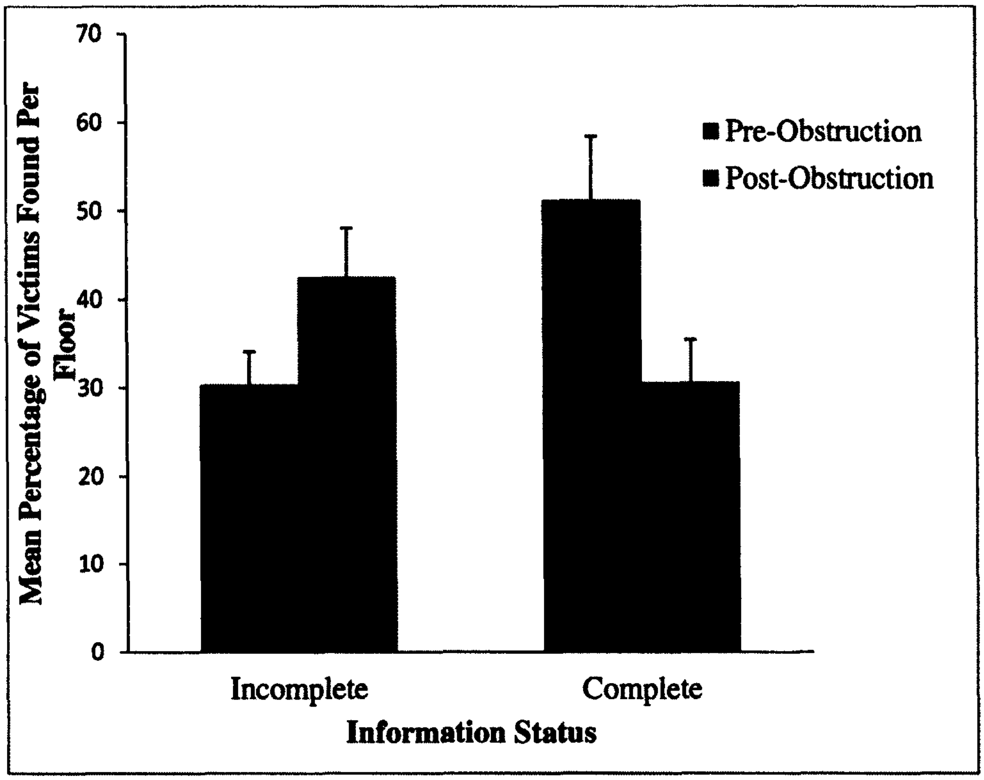


Figure 10. The interaction between information status and obstruction sequence on mean percentage of victims found per floor. Error bars reprsent standard error.

Overall Efficiency. The efficiency aspect of the performance was assessed by measuring how much time participants spent prior to encountering the obstruction versus the time left afterwards. There was no significant difference in the length of pre- and post-obstruction time. Howevere, there were significant two-way interactions between architectrual legibility and obstruction sequence, F (1, 20), $p < .001$, $\eta^2 = .49$, and also a significant three-way interaction, F(1, 20), $p < .05$, $\eta^2 = .25$.

As shown in Figure 11, the lengths of pre- and post-obstruction times depend on the architectural legibility of the search location. In the high legibility/apartment building condition, the pre-obstruction time was shorter compared to the post-obstruction time, while the opposite trend was observed in the low-legibility/office building condition. The effect size of the three-way interaction was about half the value of the two-way interaction, thus it will not be discussed in great depth. However, the visual representation of the three-way interaction is available in Figure 12.

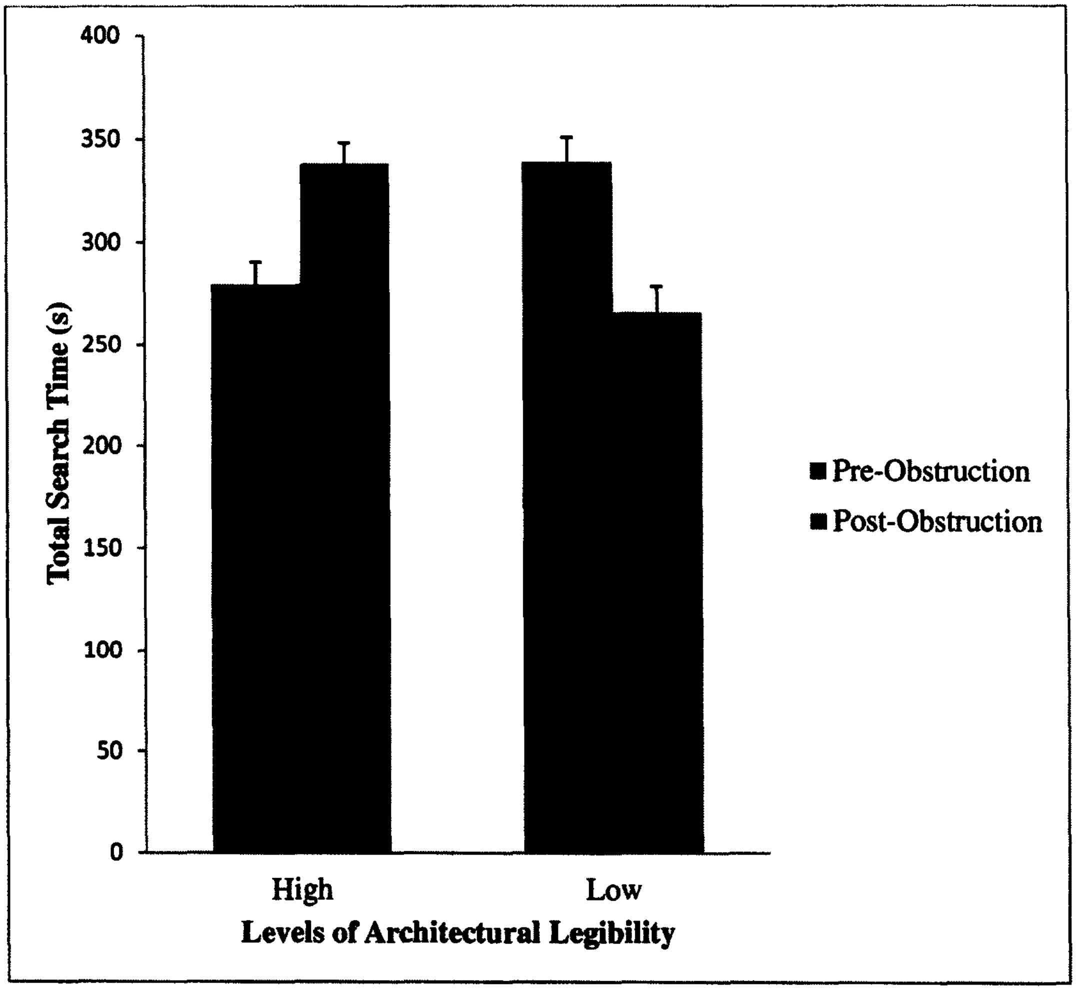


Figure 11. Interaction between architectural legibility and obstruction sequence on total search time. Error bars represent standard error.

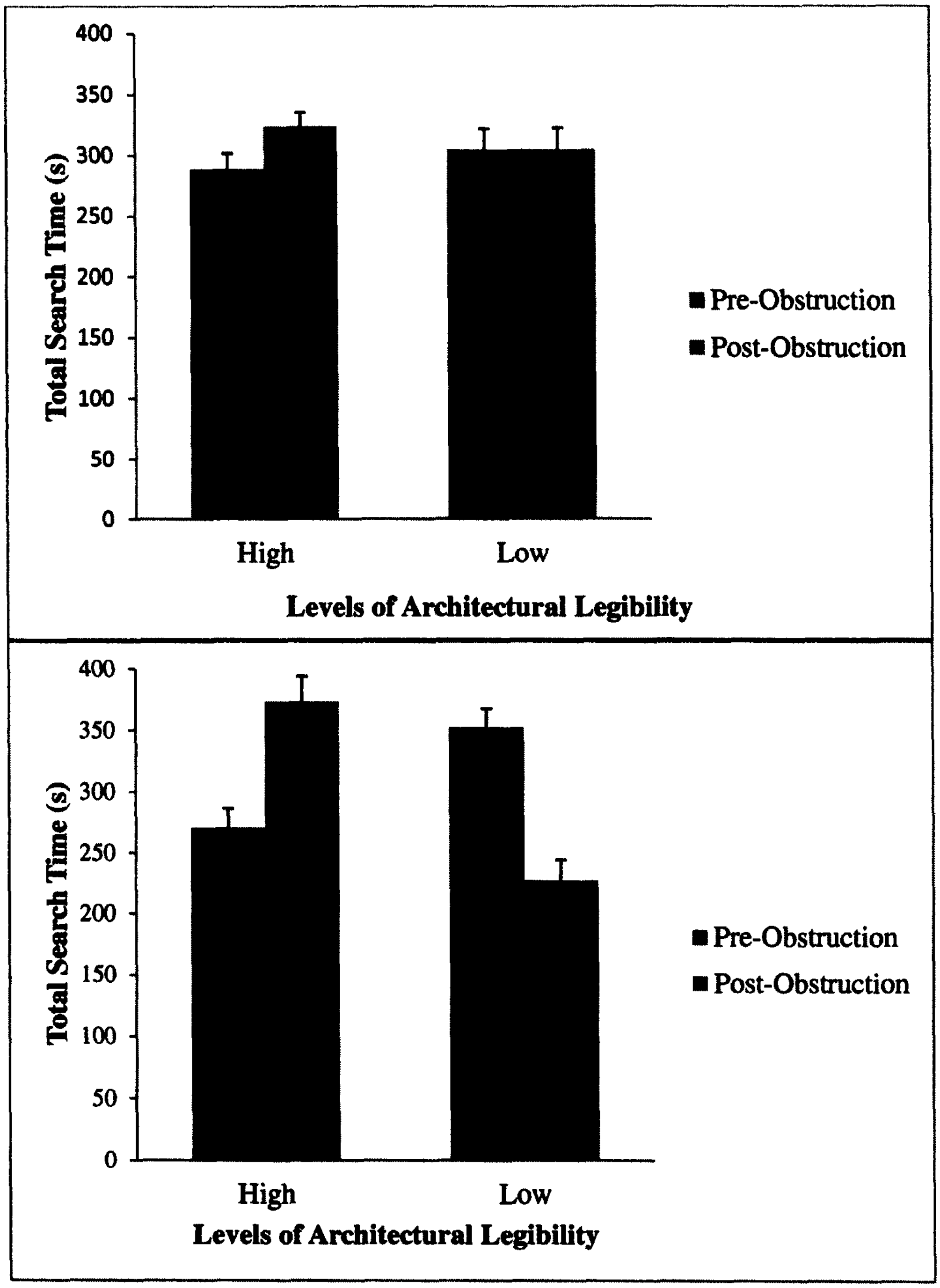


Figure 12. Three-way interaction between architectural legibility, information status, and obstruction sequence on total search time given incomplete (top) and complete information (bottom). Error bars reprsent standard errror.

Overall Efficiency Per Floor. The mean time spent per floor was also calculated to analyze the element of efficiency in the performance. Three-way ANOVA analysis showed only a main effect of obstruction sequence, $F(1, 20) = 28.57$, $p <.01$, $\eta^2 = .59$. The mean time length pre-obstruction ($M = 267.51$, $SE = 10.07$) was longer than the time length post-obstruction ($M = 210.07$, $SE = 10.29$). No interaction effect was observed.

Efficiency of Fire Search. In order to compute the efficiency of fire search per floor, the number of fires found on a floor was divided by the time taken to find them. This number was subsequently divided by the number of floors searched in order to extract a mean rate value, where a larger magnitude indicates higher efficiency.

There was a significant main effect of obstruction sequence, $F(1, 20) = 23.61$, $p < .001$, $\eta^2=.54$. Specifically, the pre-obstruction rate ($M = .026$, $SE = .002$) was superior to its post-obstruction counterpart ($M = .016$, $SE = .001$). Obstruction sequence interacted significantly with architectural legibility, $F(1, 20) = 18.20$, $p < .001$, $\eta^2 = .48$ (Figure 13). It is evident from the figure below that the decline in efficiency from pre- to post-obstruction is larger in the high-legibility/apartment building condition than the low-legibility/office building.

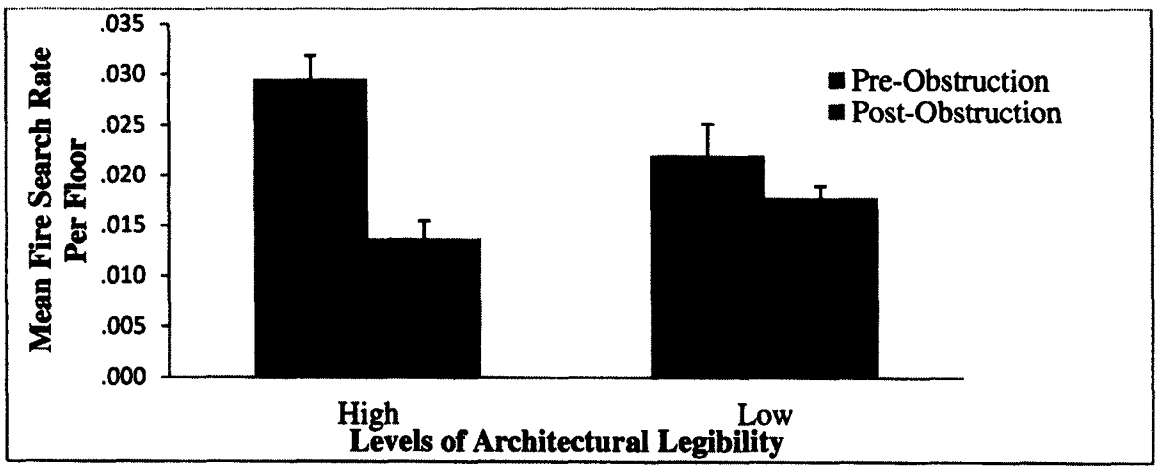


Figure 13. The interaction between architectural legibility and obstruction sequence on the mean fire search rate per floor. Error bars represent standard error.

Efficiency of Victim Search Rate. The victim search rate was calculated in the exact same manner as that of the fire search rate. No main effect was observed, but there were two significant 2-way interactions. Architectural legibility interacted significantly with information status, $F(1, 20) = 6.65, p > .05, \eta^2 = .25$ (Figure 14), and obstruction sequence, $F(1, 20) = 11.48$, $p < .01, \eta^2 = .37$ (Figure 15). As can be seen from Figure 14, the search rate in the low legiblity/office condition had significant pre-post difference compared to the high legibility/ apartment condition. Office/incomplete condition also had a higher search rate than apartment/incomplete condition. Figure 15 shows opposite pre-post difference patterns between the apartment and office buildings. The post-obstruction search rate was markedly better in the apartment setting compared to the pre-obstruction rate, whereas the reverse trend is observed in the office condition.

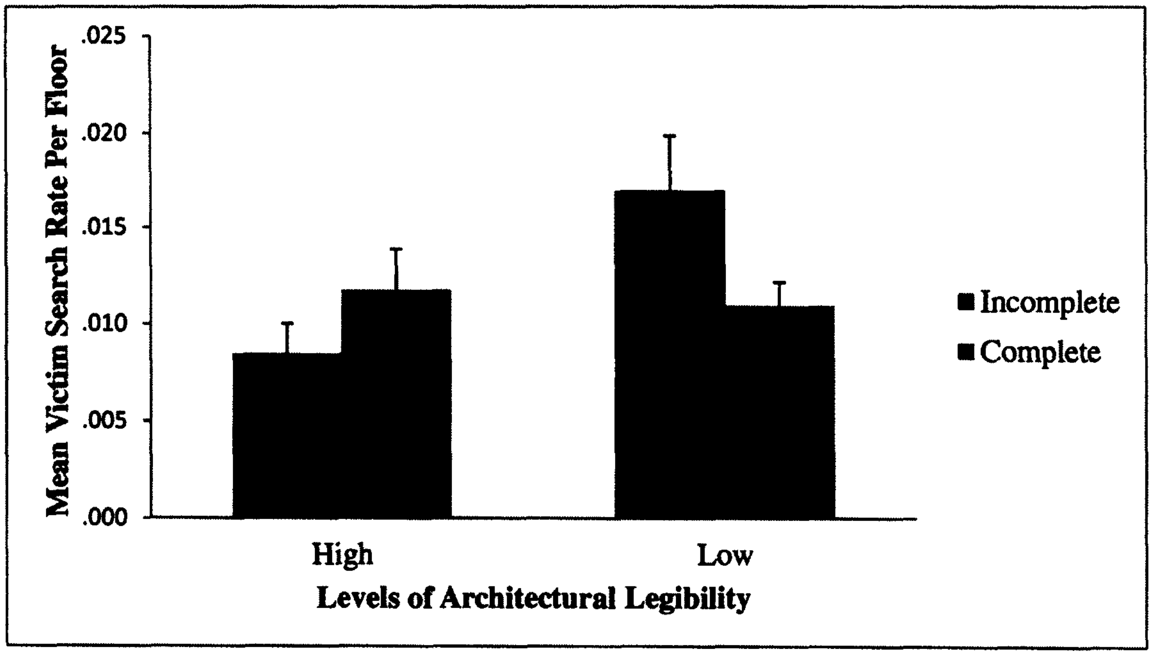


Figure 14. Interaction between architectural legibility and information status on mean victim search rate per floor. Error bars represent standard error.

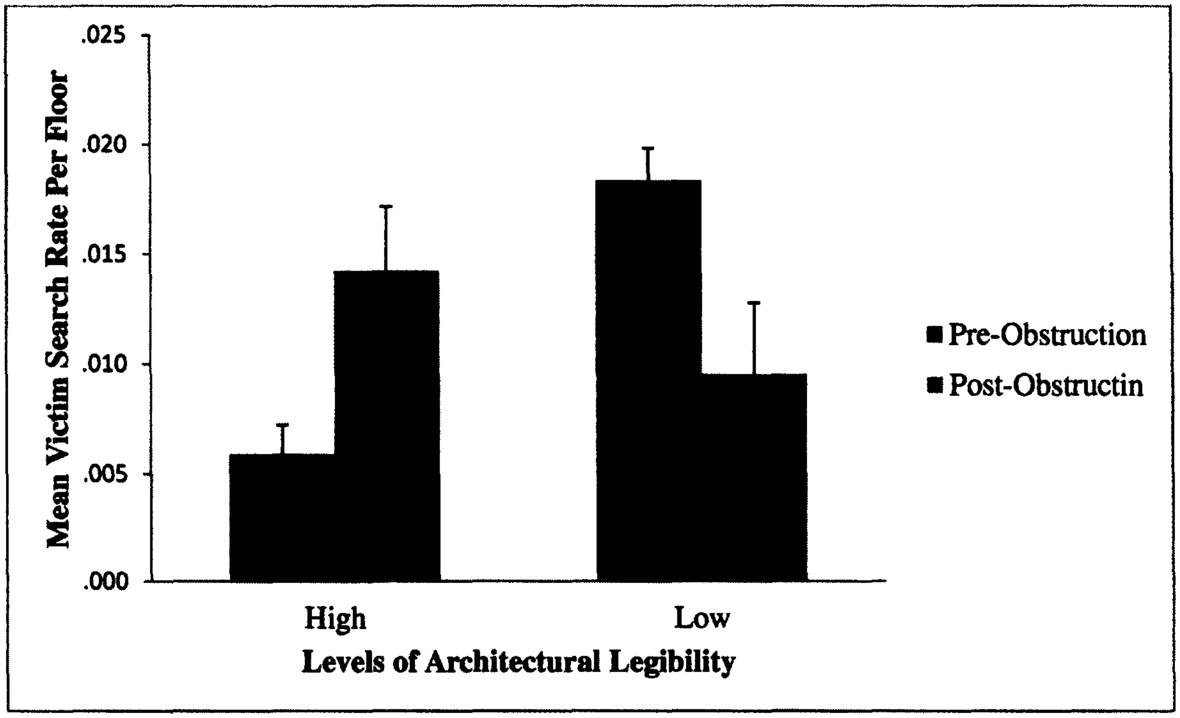


Figure 15. Interaction between levels of architectural legibility and obstruction sequence on mean victim search rate per floor. Error bars represent standard error.

Situation Awareness

The situation awareness scores were quantified in several steps. First, each correct probe response was assigned a score of 1 and incorrect response 0. As there were a total of three probes administered to participants, the number of pre- and post-obstruction probes would either be one or two depending on when participants reached the obstruction. If there were two probes prior to or after the obstruction, the scores were simply averaged. For example, if the teams had two probes post-obstruction scored 1 and 0, the mean SA score post-obstruction was 0.5. These raw scores were then subjected to square-root arcsine transformation ($Y' = 2 \text{ arcsine } (\sqrt{Y})$) to deal with the binomial nature of the data that violated the assumption of normality. Finally, the 3-way within-subject ANOVA was applied to the transformed scores in the exact same manner as it was to the performance data.

Information status had a significant main effect on the SA performance, $F(1, 41) = 7.47$,

$p < .01$, $\eta^2 = .15$, where participants had a higher mean SA score with complete information (M = 2.1, SE = .088) and lower with incomplete information (M = 1.69, SE = .11). An examination of the interaction effects revealed a significant interplay between the architectural legibility and information status, $F(1, 41) = 11.17$, $p < .01$, $\eta^2 = .15$. It appeared that information status had an effect in the high-legibility/apartment condition, but not in the low-legibility/office condition (Figure 16). Specifically, complete information seemed to enhance SA scores in the apartment-complete condition, but when the information was incomplete SA suffered. No other main and two-way interaction effects were detected. Thus, this means that there were no difference in SA scores between pre- and post-obstruction times (given the change in workload), $F(1, 41) = 1.76$, $p > .05$, $\eta^2 = .04$.

There was also a significant 3-way interaction, $F(1, 41) = 14.87$, $p < .01$, $\eta^2 = .19$, as depicted in Figure 17. In the apartment building, the pre-post SA difference was much greater with incomplete information, while the pre-post gap was larger in the office-incomplete condition. For both the apartment-incomplete and office-complete conditions, the SA scores were also greater post-obstruction. In contrasting the apartment/incomplete and office/incomplete conditions, it was evident that incomplete information was associated with degraded SA and further pre-obstruction in the apartment building, but not in the office building. Pre-obstruction SA was slightly worse in the office-complete compared to its post-obstruction SA, but the pre/post difference was negligible in the apartment-complete condition.

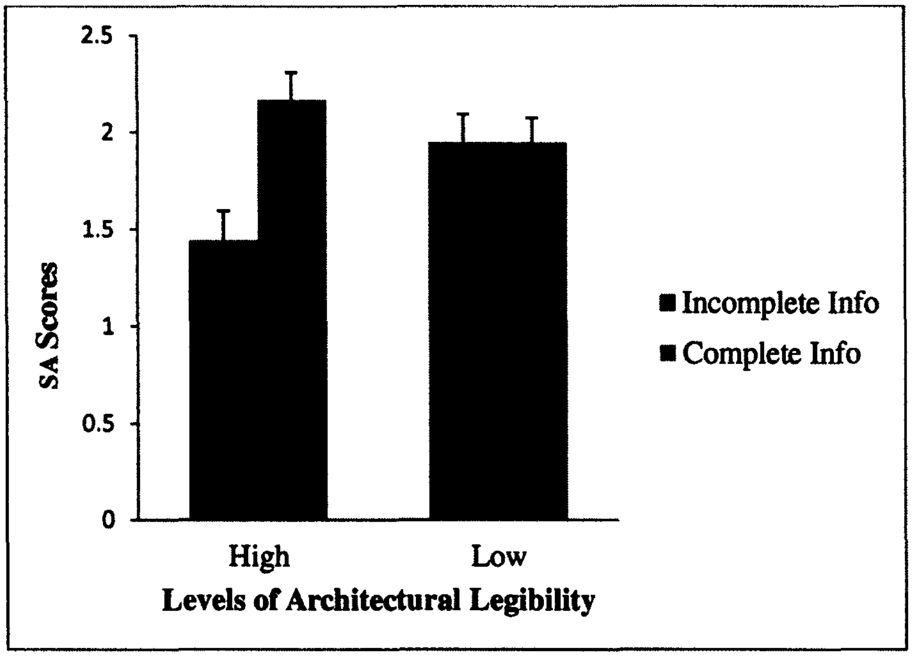
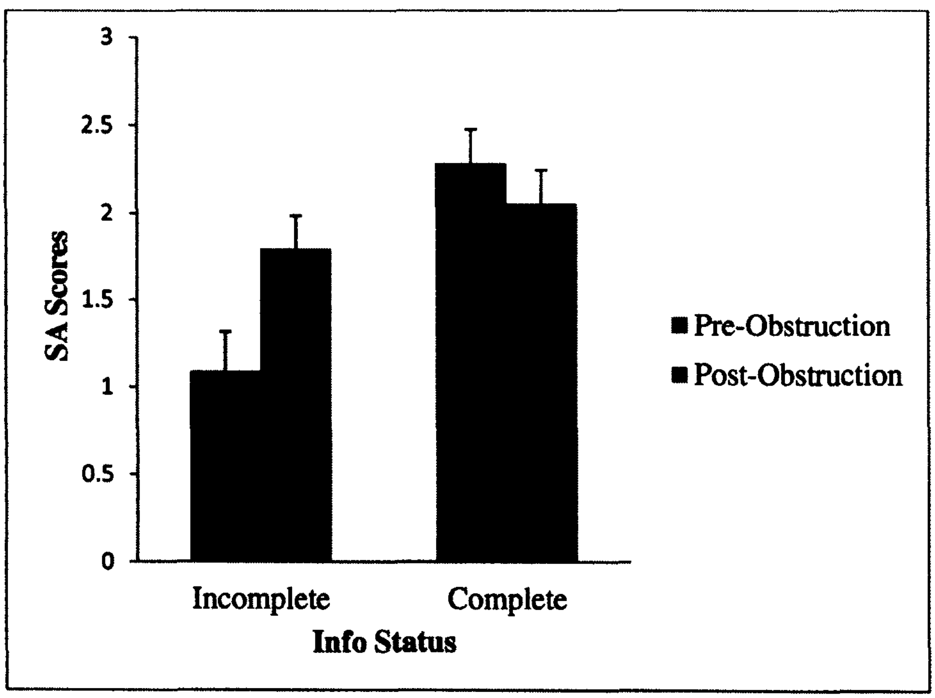


Figure 16. The interaction between architectural legibility and information status on SA probe scores. Error bars represent standard error.



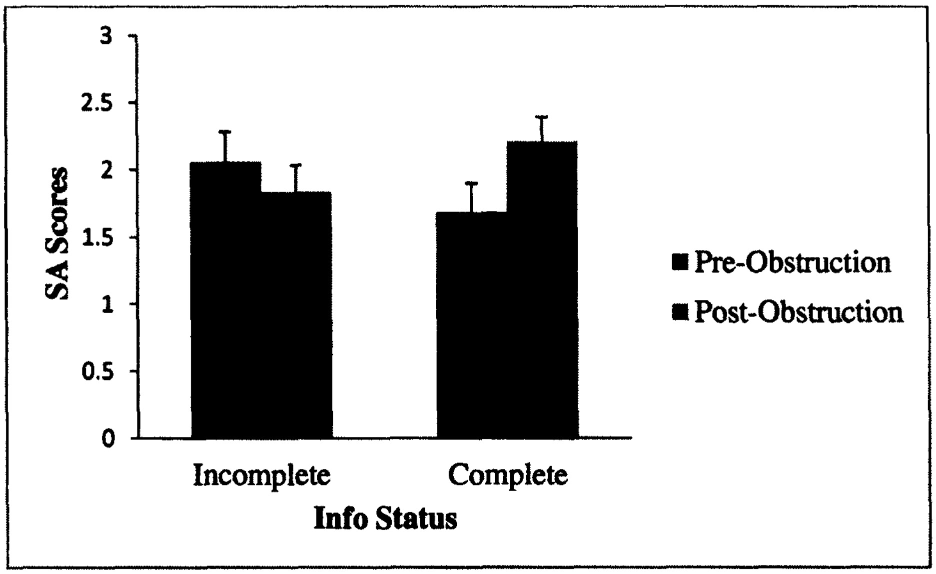


Figure 17. Three-way interaction between information status, obstruction sequence, and architectural legibility on SA scores in the high legibility/apartment building (top) and low architectural legibility/office setting (bottom). Error bars represent standard error.

Workload

The teammates' workload perception was computed with a subjective report asking participants to indicate how much work they felt they were exertingfrom a scale of 0 to 100.. The self-report was administered alongside the SA probe in a single sheet of paper and thus each person scored their workload three times. If they had two workload probes given either pre- or post-obstruction, the two values were averaged just as the SA scores were.

The three-way within-subject ANOVA did not generate any significant main effects of architectural legibility, information status, and obstruction sequence on the workload perception. There was a marginally significant effect of the obstruction sequence, $F\,(1, 41) = 3.58$, p =.66. $\eta 2 = .09$, and the magnitude of the workload score post-obstruction ($M = 67.32$, $SE = 4.64$) was greater than the value at pre-obstruction ($M = 60.04$, $SE = 2.87$).

Demographic Questionnaire

All participants filled a demographic questionnaire at the beginning of the experimental sessions. Table 2 shows a summary of how frequently team members played different types of electronic games in their daily lives. There were 8 possible choices to the gaming frequency ranging from "Several times a day" (scored as 1) to "Never" (scored as 8). On average, subjects played computer video games once or twice a month (*M* = 5.31; *SD* = 2.12), joystick-based games once or twice a year (*M* = 7.26; *SD* = 1.43), strategy games once a week (*M* = 4.38; *SD* = 2.02), and first-person shooter games around every few months (*M* = 5.69; *SD* =2.08). With the exception of the joystick type (a score of 3 means "several times a week"), participants' experiences in their gaming frequency range from "Several times a day" (highly frequent) to "Never." Participants were also asked if they were usually prone to cybersickness. There were 3 possible responses to this question which are "Yes" (scored as 1), "Sometimes" (scored as 2), and "No" (scored as 3). On average, the participants reported that they did not usually experience cybersickness (*M*=2.86; *SD* =.35) and no one reported a "Yes" response.

Table 2

Summary of Participants' Usual Gaming Experienceand Frequency

Game Types	Mean	SD	SE	Range
Computer	5.31	2.12	.33	1-8
Joystick	7.26	1.43	.22	3-8
Strategy	4.38	2.02	.31	1-8
First-Person Shooter	5.69	2.08	.32	1-8

Feedback Questionnaire

Participants were given a feedback questionnaire to assess various facets of their subjective experience with the task. Overall, teams didn't find one building setting to be more difficult then the other, $F(1, 41) = .06$, $p>.05$. They were also asked regarding how difficult it was for them to navigate and orient themselves in each environment on a scale of 1 (very difficult) to 5 (very easy). The participants found the office to be quite challenging to navigate through (M= 2.23, SE = 1.01) while the apartment building was not particularly easy or difficult to explore ($M = 3.41$, $SE = 1.25$), $F(1,41) = 22.57$, $p < .05$. Similarly, participants perceived neutral or mid-level orientation difficulty ($M = 3.50$, $SE = 1.15$), while they experienced the office building to be quite difficult to orient themselves in ($M = 2.38$, $SE = 1.13$), $F(1, 41) = 22.48$, $p < .05$.

Discussion

The objective of the study was to investigate the effects of architectural legibility, information status, and sudden change in workload on TSA and team performance in a firefighting context. It was predicted that TSA and team performance would benefit from a high architectural legibility setting and complete information status. However, sudden change in workload was hypothesized to degrade both TSA and performance. In order to address these research questions and hypotheses, team performance and TSA were measured as participants executed a search operation in a simulated desktop firefighting environment.

This chapter is divided into the performance and situation awareness sections, where each dependent variable is discussed in relation to each of the three independent variables. The discussion of the relationship between the two dependent variables will follow. Finally, the limitations of the study and future research directions conclude the discussion. The focus of the discussion is on the key findings of the study, particularly on the interpretation of a consistent data pattern.

Table 3

Key Findings for the Team Performance and Situation Awareness as a Function of the Independent Variables (Rows)

	Team Performance	Team Situation Awareness
Architectural Legibility	Higher overall performance in the low-legibility/office setting	Inconclusive relation
Information Status	Inconclusive relation	Higher TSA with complete information
Obstruction Sequence	Performance decline post-obstruction	No observed significant effect

Performance

Two facets of performance, effectiveness and efficiency, were examined with respect to searching and locating fires and victims. Effectiveness refers to success rates in discovering fires and victims, and efficiency refers to the rate as a function of time at which fires and victims were found. The patterns of the findings differ between the two facets of performance, depending on the architectural legibility, information completeness, the presence of a sudden obstruction, and whether victims or fire were found.

Performance and Architectural Legibility. Overall, participants were more effective and efficient in the office with the low architectural legibility, as compared to the apartment building with high architectural legibility. In the office building, the victim search was more effective compared to the apartment building and more efficient pre-obstruction. Encountering the obstruction did not seem to have an impact on fire search in the office building. In the apartment building, the obstruction did not have a significant effect on the overall victim search performance and the victim search was less efficient compared to the office building. Fire search efficiency and effectiveness were the most optimal in the apartment building pre-obstruction relative to post-obstruction and compared to the fire search performance in the office building.

The overall better performance in the office building was different from what was expected from the low and high architectural legibility index. Although teams performed better in the office building, they reported significantly higher difficulty in orienting themselves, $F(1, 41) = 22.48$, $p < .05$, and navigating the office/low-legibility environment compared to the apartment building, $F(1,41) = 22.57$, $p < .05$. In this respect, the participants' subjective perceptions of the environment were in line with results in ICD research (Weisman, 1981; O'Neill, 1991b). However, ICD did not significantly predict performance as hypothesized.

Since the ICD proved to be a poor predictor of performance, there is a need to find an alternative index reflecting spatial legibility. One such index is the Visibility Graph Analysis (VGA) that measures the extent of visibility from a particular vantage point (Turner et al., 2001). The higher the VGA, the larger the visual field it affords to a viewer. Li and Klippel (2010) conducted a way-finding experiment where their participants were asked to find a book in three different library locations. Each location was measured for both their VGA and ICD and the experimenters were interested in the aspect of the performance that each index predicted. While ICD positively correlated with the time taken to retrieve the book, VGA was indicative of the extra distance beyond the shortest route traveled to complete the task. In other words, lower visibility of the space appeared to lead to inefficient search strategy and this appears to be consistent with the extra turns participants took in the apartment building.

A follow-up analysis in the study here supports further the possibility that perception of spatial legibility as reflected in the ICD does not match actual performance. The number of turns that participants took were computed for the apartment and office with complete information. This was done to evaluate the efficiency of their search behaviour based on the pattern of paths they travelled, where a lower number of turns indicates higher efficiency. Given that one entire apartment floor had five more choice points compared to an entire office floor, it is reasonable to expect some differences in turning efficiency.

According to the result, participants had significantly fewer turns in the office building compared with the apartment building, ($t(41) = 3.05, p < .01$). No turn analysis was performed in both buildings with complete information. Nonetheless, it can be predicted that the turning pattern is also similar with incomplete information conditions, thus giving the overall picture that participants generally made more turns in the apartment building.

The empirical search inefficiency in the apartment building and the conceptual notion of the VGA can help explain the findings here by the fundamental spatial differences between the two building types and their impact on visual performance. The apartment building has many rooms with smaller spaces compared to the more open space in the office building. Thus, it can be argued that each vantage point in the apartment building afforded very little visibility of other parts in the building in a way that can support better search planning. In other words, the smaller spaces in the apartment building can act as a smaller FoV (field of view) with no visual horizon.

Research in the area of HMD (head-mounted displays) and FoV has shown that a narrow visual field results in longer completion times for visual search tasks (Wells, Venturino, & Osgood, 1988; Venturino & Kunze, 1989; Arthur, 2000). Particularly, Wells and Venturino (1990) found that the disadvantage of having a small FoV increases with a higher number of targets or greater task complexity. Gauthier et al. (2008) studied how night-vision goggles with a 30 degree FoV affected the performance in a navigation task. After participants performed the experiment, they were asked to complete a spatial memory test (on distance judgment) and a map sketching task to see how the restricted FoV of the goggles influeced their spatial representation of the environment. Compared to the control condition, those who used the goggles had poorer spatial memory test results and less accurate map drawings. A follow-up study by Gutterman (2009) did not find the same results with the spatial memory test, but the participants who used the device with a narrower FoV had more distored sketch maps. Taken together, these studies can be analogously applied to the performance results in the apartment building, where the smaller spaces interfered with the participants' spatial integration of the environment and thus degraded their search performance.

As fires were more immediately visible, they were easily noticed and found by the dyads. Victims took more effort and concentration to find because the smoke obstructed the visibility of the environment, and the hidden victims (often occluded by furniture as well) degraded their discovery. The issue of smoke coverage could have also contributed to the insignificant pre-post difference in victim search effectiveness, where victim search efficiency was poorer in the apartment building, particularly in the pre-obstruction phase. The smoke effect in the apartment building perhaps made it equally difficult for teams to locate victims before and after the obstruction encounter, but this was not the case with victim search efficiency. As seen in Figure 15, teams had a much lower rate of discovery in the apartment building pre-obstruction and this rate curiously improved significantly post-obstruction. Teams were less likely to find victims in the apartment building because the smoke might have significantly prolonged the time taken to find them. Once the teams got past the obstruction, they could have learned from their previously challenging experience and could have tried to be more thorough that time around, resulting in the observed efficiency improvement. The combination of more widespread smoke coverage and smaller FoV of the apartment building might explain the poorer performance in this setting.

Performance and Information Status. The effect of information completeness on search performance did not show a clear trend, as information status did not have a significant main effect for many of the performance indicators. For instance, contrary to what was expected, higher fire search effectiveness was associated with incomplete information. Given complete information, teams spent most of their searching time post-obstruction in the apartment building and pre-obstruction in the office building. Moreover, it appears that the combination of a high-legibility environment of the apartment and the complete information caused the teams to be more efficient with their fire and victim search performances.

One explanation for the inconclusiveness of the relationship between information status and performance was how complete information status unexpectedly hindered performance. When teams worked with incomplete information, they had no way of being certain that they had found all the victims and fires they had to find. On the other hand, when teams were given complete information (knowledge certainty), they kept searching and did not move on to the next location until they had found the listed victims and fires, thus lowering the percentage of target items found.

Research on the area of social cognition can shed light on how the level of informational certainty affects one's depth of information processing and explained the study's results in an analogous manner. According to Chaiken et al.'s (1989) sufficiency threshold hypothesis, people will do all that is necessary in order to feel certain about the information that they are given. As a result, they process surrounding cues more systematically, but when they have a sufficient level of certainty, they rely more on heuristic processing.

Tiedens and Linton (2001) induced in their participants emotions that are commonly associated with certainty (anger and contentment) and uncertainty (worry and surprise) by writing autobiographical essays. A post-hoc questionnaire revealed that the induced emotions produced the corresponding emotions. The participants were then asked to evaluate an essay on issues facing post-secondary institutions. In one condition, they were told that the essay was written by an expert and the researchers were interested to see if participants were more persuaded when they wrote anger- or contentment-inducing autobiographical essays. The results showed that participants were more likely to be persuaded by the expert essay (i.e., rely more on heuristic, rather than systematic processing) when induced earlier with the certainty-associated emotions. In other words, they tended to judge the essay's arguments by its logical strengths and weaknesses when they were uncertain, rather than when they were certain.

Analogously applied to the results of this study, the literature on certainty and the resulting depth of information processing may mean that informational certainty caused teams to be less thorough with their search. Without the certainty of information regarding fires and victims, teams might feel more "pressure" to be more cautious and comprehensive with their search. This "pressure" could have lessened the disadvantage that the absence of information had on performance. On the other hand, the teams' excessive reliance on the complete information (analogous to certainty and its associated heuristic processing) conditions caused them to be less thorough with their search. When they didn't find the listed victims and fires, they then became too "caught up" in what they missed, so that they became less careful with their overall searching progress.

Performance and Obstruction Effect. Obstruction had the most consistent impact on both effectiveness and efficiency of the search, where the dyads did better before encountering the obstruction as compared to after the encounter. The effect of encountering the obstruction on performance is consistent with previous findings showing that performance is reduced following a workload shift (Cummings & Croft, 1973; Matthews, 1986; Cox-Fuenzalida et al., 2004). This difference between pre- and post-obstruction performance was particularly pronounced in the apartment building. In other words, performance in the apartment building declined post-obstruction more than post-obstruction performance in the office building.

A look into the overall efficiency and efficiency per floor data can help explain the post-obstruction performance difference between the apartment and office buildings. Overall, teams spent most of their search time in the apartment building after encountering the obstruction, whereas search time was longer in the office building prior to obstruction encounter (see two-way interaction in Figure 11). It raises the question of why they found fewer victims and fires if search time was longer after encountering the obstruction in the apartment building. In order for teams to find victims and fires in the apartment building after encountering the obstruction, they had to exit the building and re-enter it through a different entrance. In the office building, overcoming the obstruction required teams to find a different route on the same floor. Thus, the time taken to exit and re-enter the apartment building to overcome the obstruction consumed some of the time they could have used to find victims and fires post-obstruction. The data on the overall efficiency *per floor* in the apartment building showed a main effect of obstruction sequence, and search time per floor was longer before obstruction encounter. This can mean that on average, the time spent per floor post-obstruction in the apartment building was shorter than before the obstruction encounter because the time spent outside the building reduced the time left to search indoors. As a result, teams found fewer victims and fires post-obstruction in the apartment building compared to post-obstruction in the office building.

Teams reported that they perceived more workload after encountering the obstruction, but the difference was marginally significant. Therefore, teams did not subjectively experience a mental workload shift although their performance deteriorated post-obstruction on average.

Given the small effect size of this workload result and power = .46, a lot more participants had to be recruited in order to reach full significance. Yeh and Wickens (1984) reported that poorer performance was often associated with higher perceived difficulty of the task. However, there is also evidence for a dissociation between performance and subjective workload in the literature. Tulga (1978) found that easing the performance criterion of a task corresponded with a lower level of reported subjective workload. Wickens and Derrick (1981) and Wickens and Yeh (1983) found that participants reported a higher workload when doing two concurrent easy tasks, rather than one single hard task, although the performance was better with the easy dual task.

Situation Awareness

Situation Awareness, Architectural Legibility, and Information Status. It was hypothesized that TSA would be better in an environment of high architectural legibility and with the participants given complete information. Based on the results, TSA was indeed overall better with complete information, particularly in the apartment building. The relation between complete information and TSA is consistent with the literature that generally suggests complete information benefits SA (Endsley et al., 2000; Parush et al., 2011; Wauben et al., 2011). However, the TSA scores in the office building remained consistently high regardless of the levels of information completeness and the effect of architectural legibility on SA was less conclusive.

Incomplete information appears to have substantially lowered the mean SA in the apartment building, even compared to the results in the office building . Spatial awareness is proposed to be a necessary component of SA (Hale et al., 2009l; Gugerty, 1997; Wickens, 2002; Bolton & Bass, 2009). People have better way-finding performance with higher legibility surroundings (Passini, 1984; OèNeill, 1991a; Weisman, 1981). On the other hand, low legibility floors impaired way-finding performance in a cognitively demanding manner (Holscher et al., 2005), making it likely that fewer mental resources are left for the individual to maintain SA. As previously discussed, a follow-up analysis shows that participants' travel paths were more inefficient in the apartment building. Thus, the effort to repeatedly locate missed victims might have competed with the cognitive resource to sustain SA. The addition of information inadequacy might interact with the stress of this inefficiency to further reduce SA quality.

SA and Workload. In this study, workload shift did not significantly degrade TSA post-obstruction as expected. The relationship between SA and workload has been shown to be nonlinear and inconclusive in the literature (Endsley, 1993; Vidulich, 2000; Saner et al., 2009; Ma, 2012). According to Endsley et al. (2000), poor SA is possible even with low and moderate workload levels and the two constructs may be independent of each other, being only related under select circumstances.

Figure 1 depicts a visual representation of the non-linear relationship between SA and workload proposed by Endsley and Jones (1997), where SA only declines when workload level rises to a certain threshold level. It is possible that sudden workload shift induced by the obstruction did not increase workload enough to reach such threshold in accordance with Endsley and Jones's (1997) model. A follow-up analysis of the perceived workload scores (a scale of 0 to 100) revealed that teams had workload only slightly higher than the mid point (M = 62.95, SE = 2.78). The average increase in perceived workload in the pre- to post-obstruction time frame only reached marginal significance. Therefore, this may mean that the obstruction designed was not challenging enough for the participants.

SA and Performance

The results of the study did not show a consistent relation between SA and performance.

It was hypothesized that a higher SA would positively correlate with better performance as some studies have found such a trend (Entin & Entin, 2000; Roth et al., 2006; Sulistyawati et al., 2009), but according to Endsley et al. (2000), SA merely increases the chance of a higher performance, but does not guarantee such results. For instance, Endsley (1988) found the SA of pilots using a new avionics system to be better than the SA of pilots who used an older system, yet there were no differences found in the two groups' performance. Other factors such as decision making, working memory, attention, and experience affect the relationship between SA and performance (Endsley et al., 2000). In the future, a more in-depth look into these types of variables in addition to information availability should help to further clarify the relationship between SA and performance.

Additionally, some of the knowledge tested by the SAGAT probes might not have been indicative of knowledge that contributed to the overall search performance quality (similar to the previously discussed ambiguity between SA and information status). For instance, level 1 SA probes asked participants about the number of victims and/or fires that had been located thus far. Performance level was evaluated based on the number of victims and fires that were found, and thus the accuracy of the responses might predict better performance, but not always necessarily so. For instance, one of the teammates could spot a victim, but did not communicate it with his or her teammate. As a result, their SA response to a level 1 statement such as, "A fire or a victim has been detected," would differ, but as a team, they had technically found a target item. The same can also be said of some level 2 statements such as, "None of the victims in this unit is in the same room as the fire." In order to perform well, all they had to do was to locate the victims, thus keeping track of where the fires were in relation to the victims might not have been relevant to the goals of the task. A post-hoc Chi-square analysis did not show any statistically significant results on the effects of the SA level questions and the tally of disagreeing responses, X^2 (2, N =21), p >.05, but teams tended to have a higher level of response disagreement for levels 2 and 3 SA probes compared to level 1 probes. This could have contributed to the overall disconnect between the SA and performance results.

Practical Implications

TSA and Real-Life, Spatially Complex Environments. Teams from various domains and disciplines such as firefighting, military, and tactical SWAT cope with built and outdoor environments with varying levels of environmental complexity (Jones & Hinds, 2002; Chiasson et al., 2003; Ruppel et al., 2010). The structural characteristics of one's surroundings are reflected and processed at the cognitive level (Penn, 2003). Therefore, further empirical studies regarding the interaction between SA and space syntax can potentially inform and improve the practices of the abovementioned fields to maximize performance.

An integral part of situation awareness is the ability to perceive, comprehend, and project the spatial elements of the environment to holistically interpret a given situation (Hale et al., 2009). Research on the relationship between spatial cognition and SA has mainly focused on the importance of awareness of the spatial elements of the environment critical to the task at hand (Milham, 1996; Gugerty, 1997; Wickens, 2002; Bolton & Bass, 2009). However, the investigation into the effect of the physical structure of the environment and its influence on SA seems scarce. This study shows that the relationship between SA and architectural legibility to be inconclusive. Nonetheless, extensions of this study are necessary in order to further understand how the two constructs are related to each other precisely.

Firefighting Tactics Training. This study was conducted within the context of the firefighting domain and is intended to enrich its practices in knowledge and applications. Unlike a real-life fire emergency situation, participants' tasks were limited to locating victims and fires, but not rescuing and extinguishing them, respectively. Still, this present study has useful implications because a firefighting team has to first locate these targets before they can alleviate the situation (Goodson & Murnane, 2008).

One surprising result from this study is how complete prior information regarding fires and victims impeded performance rather than facilitated it. This may be because knowledge of unaccounted-for victims kept participants from proceeding to search other floors. This implies that participants were "obsessed" with the information that they were given. However, search and rescue in practice cannot always be completed or even be possible at all when the fire has become uncontrollable (Ottawa Fire Services, 2010). A similar study should be conducted with firefighters to see how having such information influences their strategies and performance. If the reduced uncertainty backfires in real life as it did with the participants in this study, training and tactical manuals should devise methods and techniques to prioritize, manage, and cope with such knowledge.

Firefighters adjust their teamwork and coordination to the types of building they work with (e.g., whether it's a mall, a house, or a high-rise, etc.) (Ottawa Fire Services, 2010) for two reasons. First, different buildings have different construction materials which interact with fire in their own distinct manners. Second, the physical characteristics and exterior of the buildings will affect how the firefighters access the premises. For instance, the team will not enter a high-rise apartment complex and a shopping mall in the same manner because a typical shopping mall does not usually have as many windows as an apartment building. However, it is less clear how they are trained to cope with interior floor plans of varying complexity. Since the participants found the less legible building to be harder to navigate and orient themselves in, it is possible that firefighters will have the same perception with floors of complex confligurations. Therefore, more emphasis on how firefighters should work with different levels of architectural legibility is encouraged.

Limitations

Gaming Experience. There was a very diverse range of gaming experience for the participants in this study. As performance results were scored by dyads rather than individually, it becomes difficult to see if victims and fires were all or mostly found by one of the team members that likely play games more frequently in real life. In future studies, it may be helpful to recruit team members with more similar levels of gaming experiences to better assess their teamwork and associated performance quality.

Ecological Validity. This study recruited undergraduate university populations, meaning that the results are not necessarily applicable to firefighters. First, the tasks were simplified to fit non-professional students,. Second, the teams in the study consisted of only two members, while one unit of firefighters that goes inside the premise has one commander with 2-4 subordinates. Third, a firefighting crew has a clear chain of command (Messier, 2011), while the two team members acted as two firefighters of equal rank and identical task roles.

XVR Limitations. XVR provides a high degree of visual simulation through its first-person viewpoint and realistic design of the environment. However, it also has several fidelity issues that can reduce its applicability to training and real-life emergency situations. For instance, fires do not spread and cannot be extinguished, while victims cannot be extricated in order to be rescued. Ideally, high-fidelity software should be able to mimic as many characteristics of real fire incidents as possible to enhance its usefulness.

Factors inherent in the programming of the XVR software contributed to some of the unexpected results in the study. First, the program limits how many fires, victims, and how much smoke could be placed in the scenario and above this limit, the scenario could not be saved. Second, fires, victims, and smoke on higher floors would be visible to the experimenter when viewing a lower floor. This becomes problematic when smoke of different floors vertically overlap as it completely occluded the visibility of the firefighter avatars and victims on the lower floors. As a result, the placement of the victims and smoke had to be arranged in a strategically non-overlapping manner.

There was a difference in the instructions between the search for the office and apartment building. In the apartment building, fires, victims, and smoke were placed on specific units of living quarters on three floors that did not vertically overlap with each other. It was emphasized in the instructions for participants that fires and victims were present in particular units of living quarters (i.e., clustered). On the other hand, the office building in the software (and in real life) was not arranged by an equivalent unit of space, and thus fires and victims were not as clustered and participants were asked to search each floor in its entirety in general.

Smoke covers an entire apartment unit that is on fire and in turn, all victims in the same unit. In the office building, smoke cannot cover all surfaces of each floor due to both the software's memory limit and the restriction to avoid vertical overlap with smoke on floors above and/or below. Thus, some of the victims in the office were not covered by smoke and were easier for the teams to find. Thus, this issue serves as an additional explanation of why more victims were discovered in the office building.

While the software has been used for training purposes by firefighters in the UK and Estonia (E-semble, 2011), it has not been used in an empirical context prior to this study (Keown, 2011). Thus, it will be interesting for this software be utilized in academic settings with real firefighters to see if it helps to improve their real-life performance.. Nevertheless, due to the abovementioned, severe lack of realism with the fires, victims, and smoke, the usage of other higher-fidelity and user-friendly software is recommended.

Future Directions

Alternatives of ICD. ICD quantifies the topological complexity of a floor design through the connectivity of its various choice points (Li & Klippel, 2010). A study by Holscher and Dalton (2008) indicates that ICD has the highest internal validity as a spatial complexity measure, but it is possible for two structures to have identical ICD values, yet different perceived complexity. As previously discussed, ICD does not capture the openness of the structure's visual field quantified by VGA. The shape of the structure also matters because a straight line and a spiral have the same ICD value of 1, but the circular convolution of the spiral makes it seem more difficult to navigate (Werner & Schindler, 2004). It will be interesting to conduct a way-finding-firefighting study with structures of identical ICD and different perceived complexity to see if the performance would not differ or change due to the subjective evaluation of navigational difficulty.

While ICD has been shown to be a very useful measure of architectural legibility, it is not the only index of its kind (Werner & Long, 2003; Holscher et al., 2005). Other spatial complexity indices deserving further research include symmetry (O'Neill, 1991b; Baskaya et al., 2004), axial lines, convex spaces (Hillier & Hanson, 1984), convexity (Batty, 2001), and topological loops (Holscher & Dalton, 2008). These other measures could be combined with ICD in order to see which of them is the most predictive of way-finding performance, particularly in a firefighting or emergency-response context.

Team Communications. Communication is crucial for the success and quality of teamwork processes, including team situation awareness (Sonnenwald & Pierce, 2000; Leonard et al., 2004). This is especially important for teams with distributed team members such as the firefighting crew (Stanton et al., 2006). Therefore, a study investigating the interaction between architectural legibilit and information status as a function of the teams' communication quality can benefit the literature in this field. It will be particularly interesting to see if navigationally-related communication significantly affects the search performance and TSA.

Chain of Command. As the two team members were assigned identical tasks and had the exact same rank, their situation awareness should overlap considerably with earch other. Considering that a firefighting crew has a clear organizational structure with various sector members assigned different responsibilities, each individual's SA may be unique to each sector member, but may still overlap compatibly with the SA of members of different sectors (Martin & Flin, 1997). In order for the research in this field to be as useful as possible in the naturalistic setting, this study should be replicated with the multiple team members having different roles and organizational rank.

Additional Directions. In addition to the three suggestions above, some future research directions which were mentioned in the discussion also deserve consideration. First, the study should be replicated while taking into account variables that are known to influence the effect of SA on performance (e.g., experience, decision-making skill, working memory, and attention). Second, it should be examined if types and levels of information availability benefit certain levels of SA more than others. Third, there need to be more studies on the interaction between various space syntax methods (including ICD) and SA to fill a gap in the research literature. Fourth, this study should be replicated with firefighter participants to increase its ecological validity and to see if the observed effects of information availability on the students in this study also apply to firefighters. Fifth, a more selective inclusion criteria should be implemented in the future by recruiting team members with similar level of video game experience.

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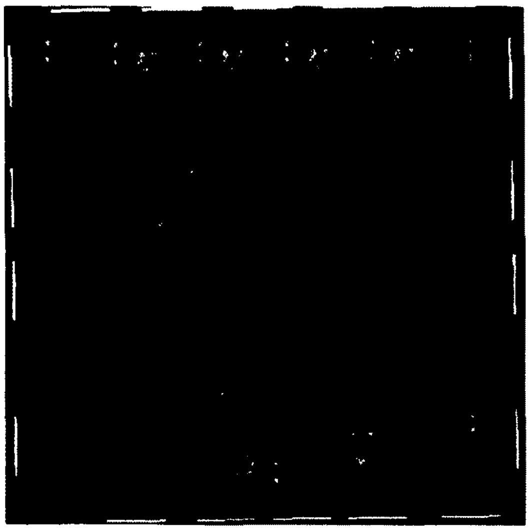
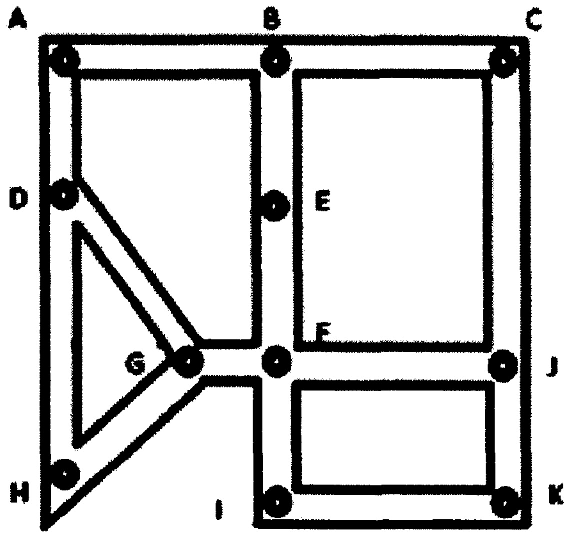
Appendix A - ICD of Office and Apartment Floor Plans

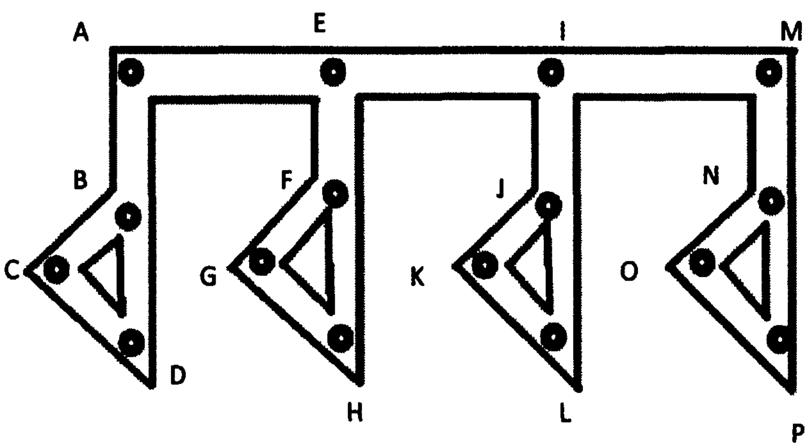
The Layout of Floor Plan Configuration in the Office Building (Reminder: all six floors used for the office scenarios have the same layouts)





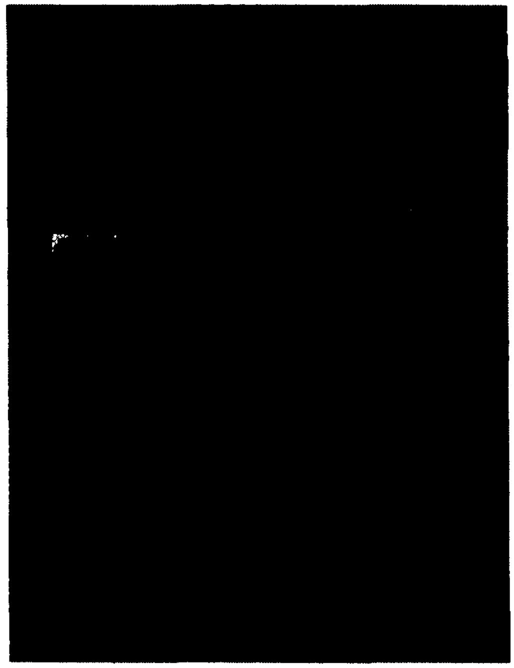
A = 2
B= 3
C = 2
D = 3
E = 2
F = 4
G = 3
H = 2
I = 2
J = 3
K = 2
Sum of A to K = 27
Total choice points =11
Mean ICD of each office floor = 27/11 = 2.45

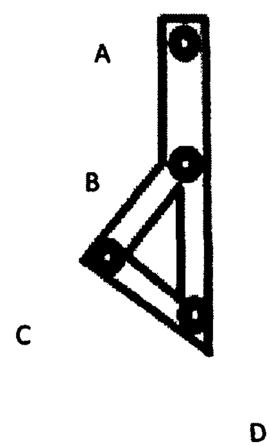
ICD Calculation of The Entire Apartment Floor



A = M = 2 → 2 X 2 = 4
I = E = 3 →3 X 2 = 6
B = F = J = N =3 → 3 X 4 = 12
C = G = K = O = 2 → 2 X 4 = 8
D = H = L = P = 2 → 2 X 4 = 8
Sum: 36
Total choice points = 18
Mean ICD for an entire apartment floor (4 units + corridor) = 36/18 = 2.38

ICD Calculation for A Single Apartment Unit





A = 1
B = 3
C = 2
D = 2
Sum = 8
Total choice points: 4
Mean ICD per apartment unit = 8/4 = 2

Appendix B - Scenario Details

Experimental Condition: Apartment-complete

Location	# of fires	# of victims
3^{rd} floor unit on fire	1	2
Stairway between 3^{rd} and 2^{nd} floor	1 (this is obstruction fire)	N/A
2^{nd} floor unit on fire	1	2
1^{st} floor unit on fire-second from the staircase	1	1
1^{st} floor unit on fire-fourth from the staircase	1	3

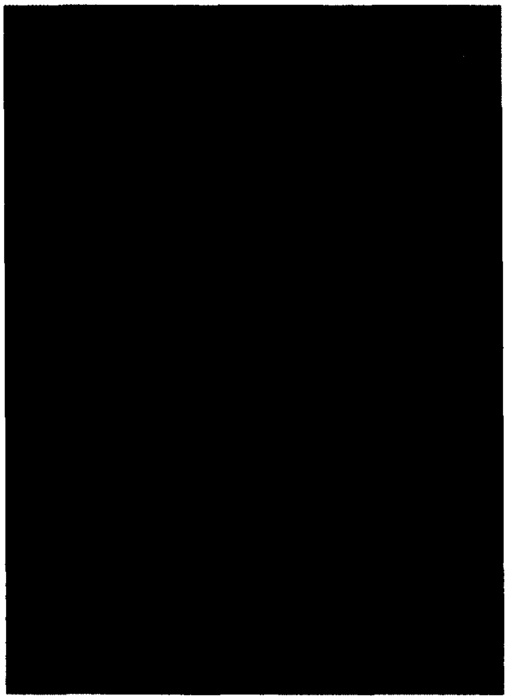
Total Fires: 4
Total Victims: 8

Location	Victim Distribution	Fire Location in the Unit
1^{st} floor unit on fire	1 woman lying in the bathtub and another woman under a bed	Fire occupies the bedroom with the woman under the bed
2^{nd} floor unit on fire	1 boy under 2 living room chairs	Fire occupies a bedroom and its neighboring bathroom (through the wall)
3rd floor unit on fire (2^{nd} from staircase)	1 elderly lady sitting on the floor in a bedroom and 1 elderly man in the bedroom across on the bed	Fire occupies the kitchen and its neighboring bathroom (through the wall)
4^{th} floor unit on fire (4^{th} from staircase)	1 woman lying under the kitchen's table, 1 woman in a corner of the living room, and 1 person under a bed	Fire occupies the bathroom with the bathtub

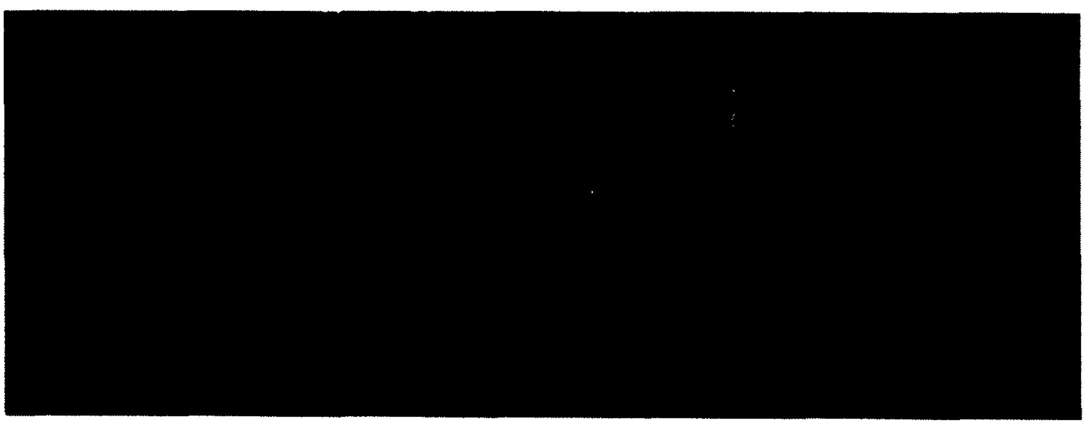
Please see Appendix K for the full mission plan instruction given to the participants. With the incomplete information condition in the apartment setting, participants are not told the number and locations of both fire and victims. In the mission plan, we instruct participants to climb a ladder (provided in advance) to a third floor apartment unit that is on fire. After finish searching that unit, they must go down the stairs to floor 2 and finally floor 1 to search the other three units specified in the mission plan. The obstruction fire is placed on stairway to the 2^{nd} floor from the 3^{rd} floor. Therefore, teams must find another way to get to the bottom two floors. The solution is by entering the 3^{rd} floor unit (that they enter from the ladder), climb it down, and enter the apartment from the ground floor from any three of the four points of egress (we block one of the four to prevent practice effect) in the apartment building: garage, east emergency exit, and main lobby entrance. We did not explicitly tell the participants about the alternative entry and exit points as this is something they must explore on their own to solve the problem as a team.

Apartment-Complete-3^{rd} floor unit on fire-next to staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

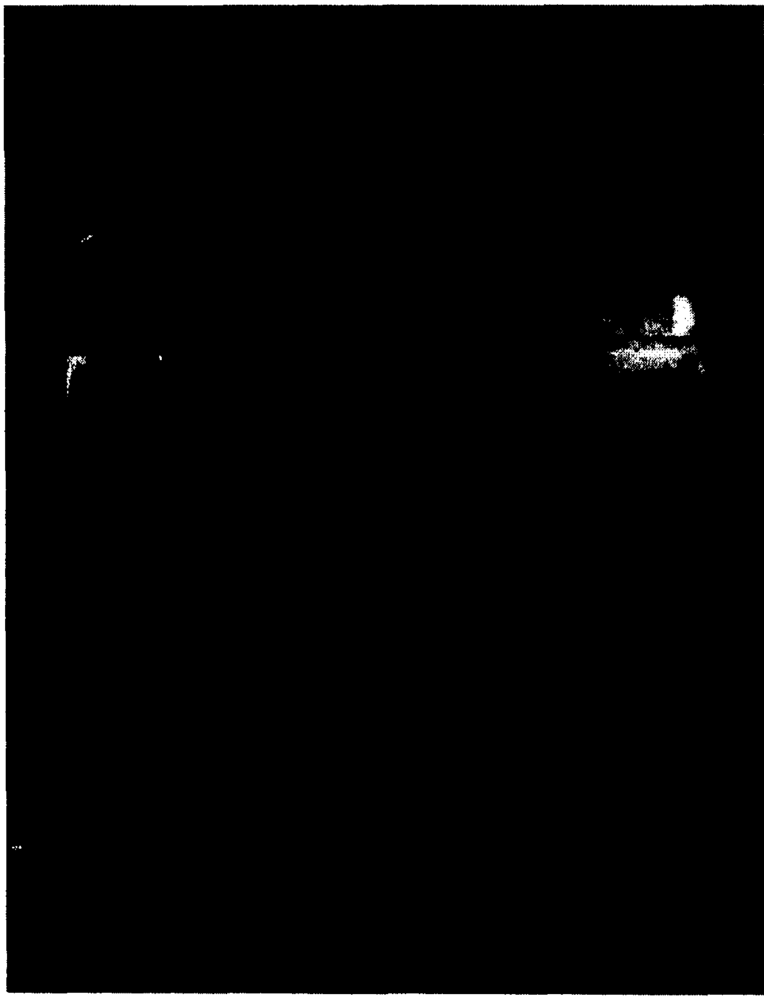
Fire



NOTE: The two photos were taken from the same apartment unit. The photo on the left reflects the environment experienced by the participants. The right photo and the rest of the photos in this appendix were taken with bright weather settings for clarity.



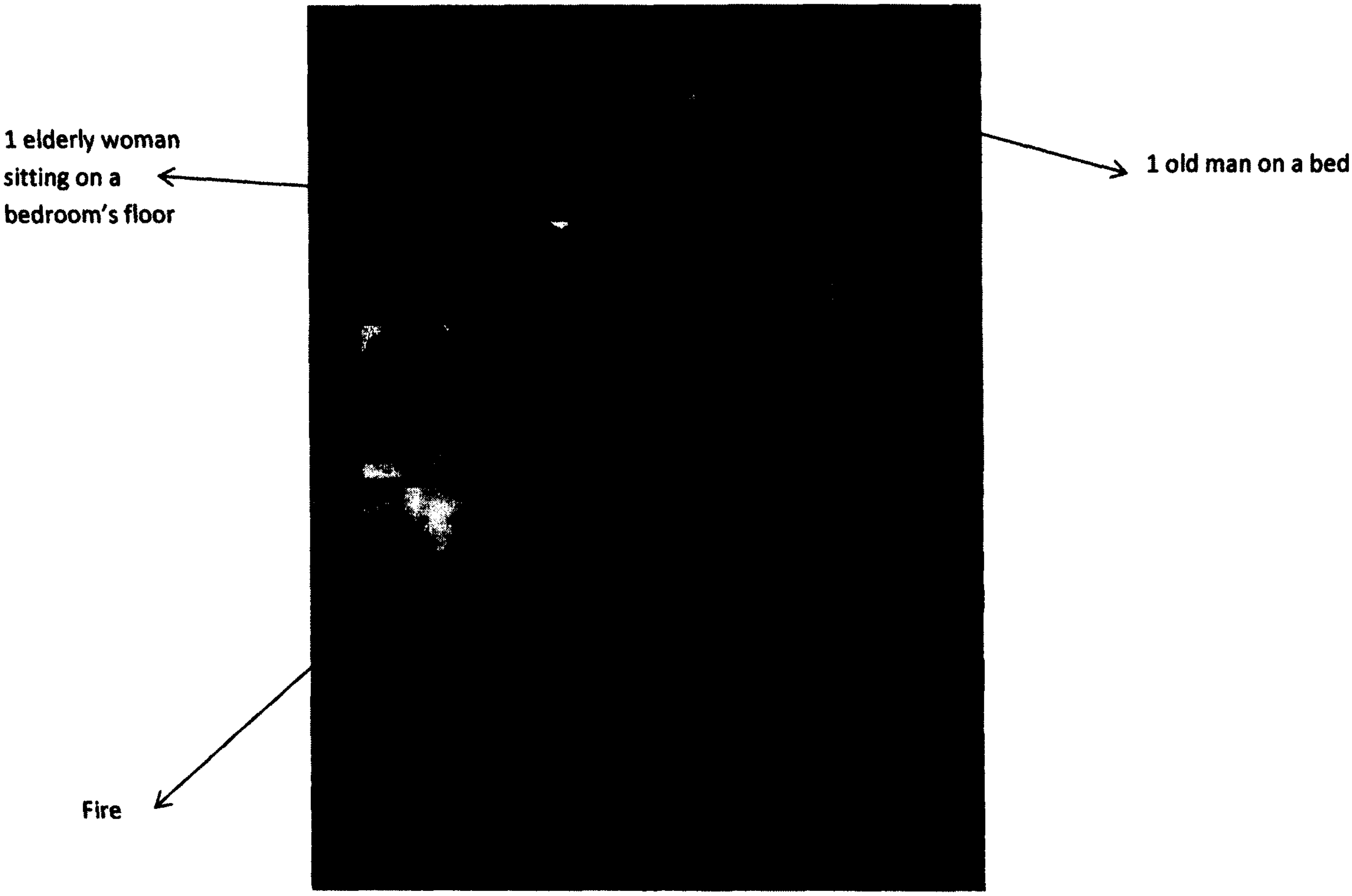
Apartment-Complete-2nd floor unit on fire 3rd from staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

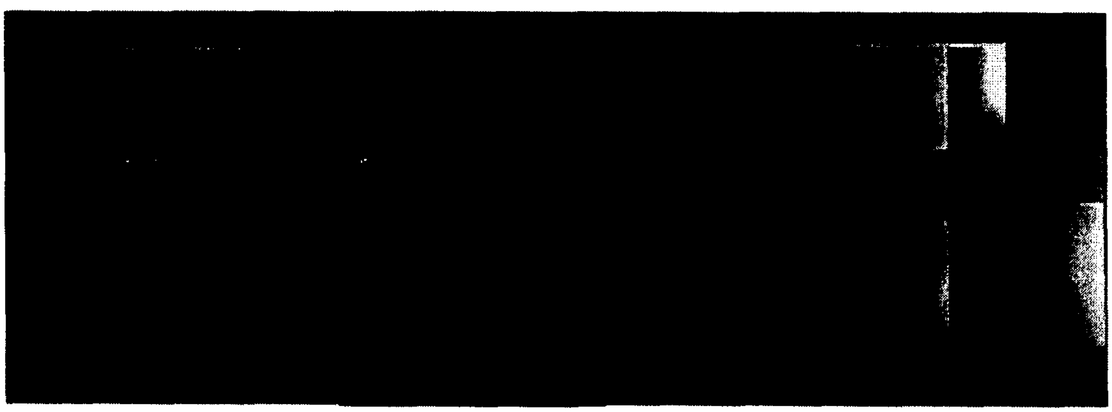


Fire

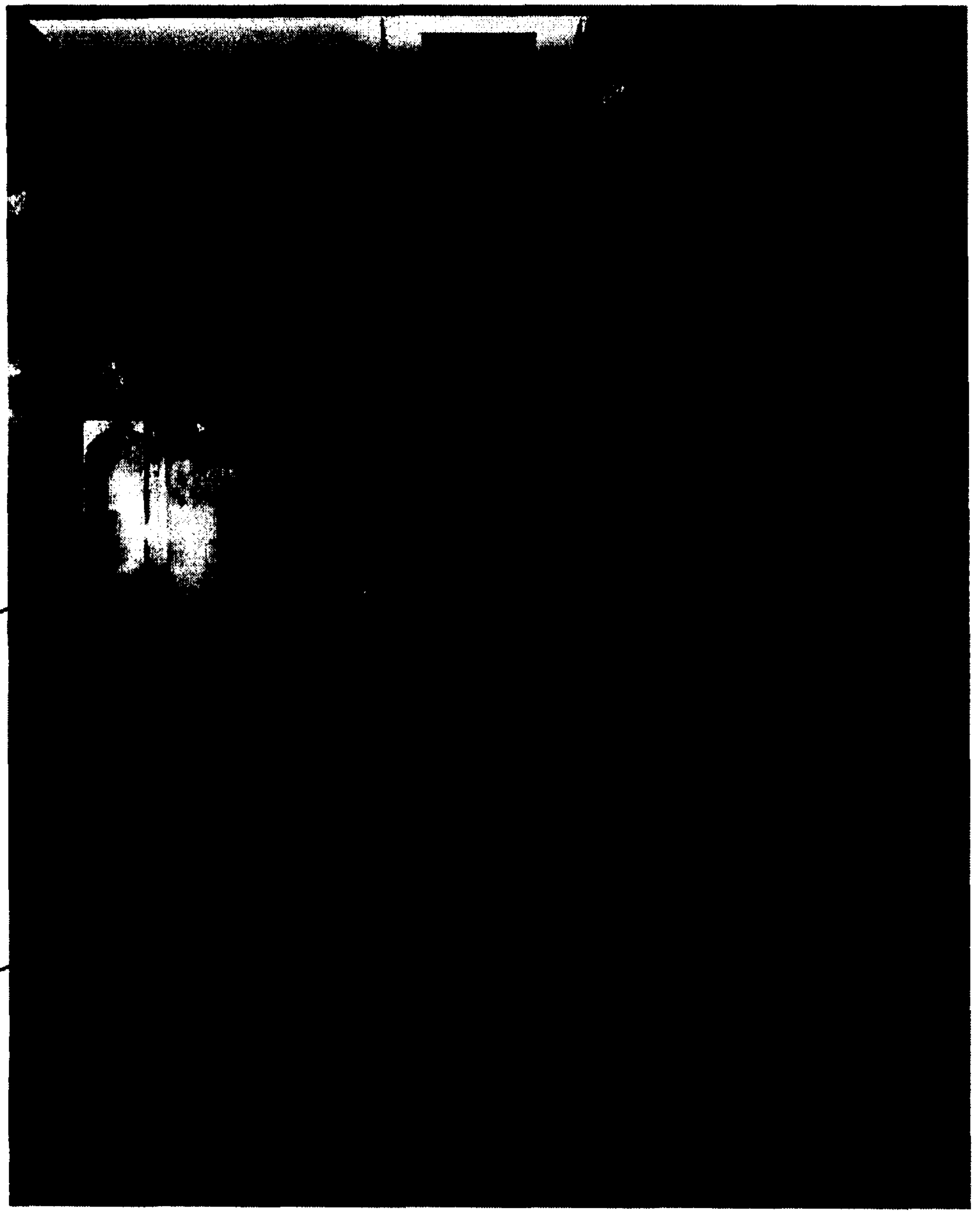
1 boy under 2 living room chairs

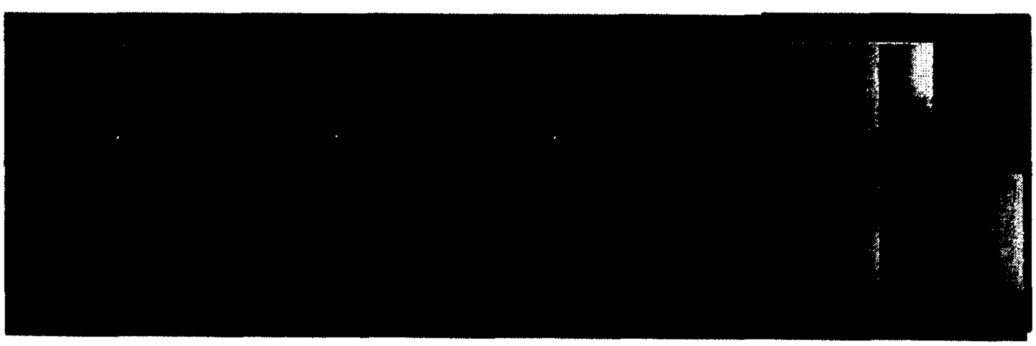
Apartment-Complete-1st floor unit on fire, 2nd from the staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)





Apartment-Complete-1st floor, 4th unit from the staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)





Experimental Condition: Apartment-complete

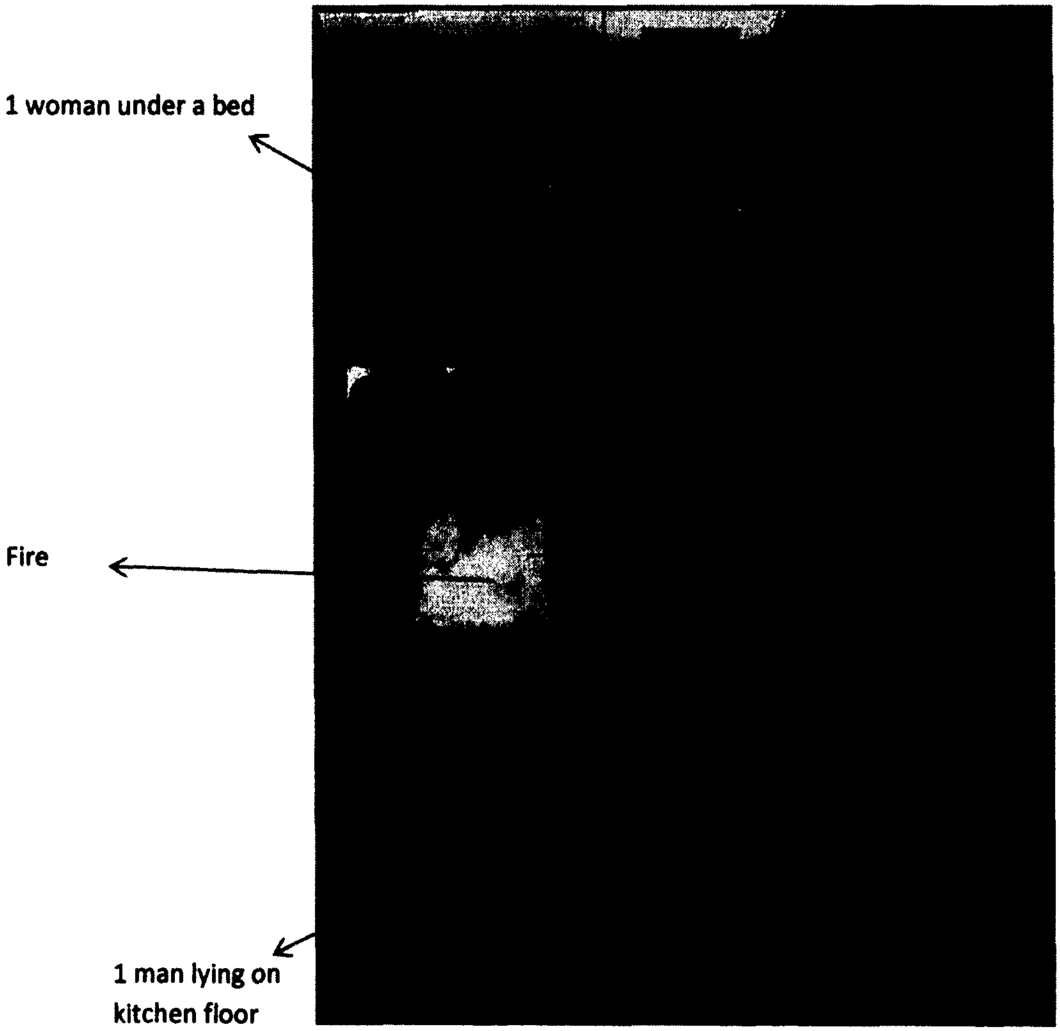
Location	# of fires	# of victims
1st floor unit on fire	1	2
On the stairway connecting the 1st and 2nd floor	1 (this is an obstruction fire)	N/A
2nd floor unit on fire	1	1
3rd floor unit on fire-second from the staircase	1	2
4th floor unit on fire-fourth from the staircase	1	3

Total Fires: 5
Total Victims: 8

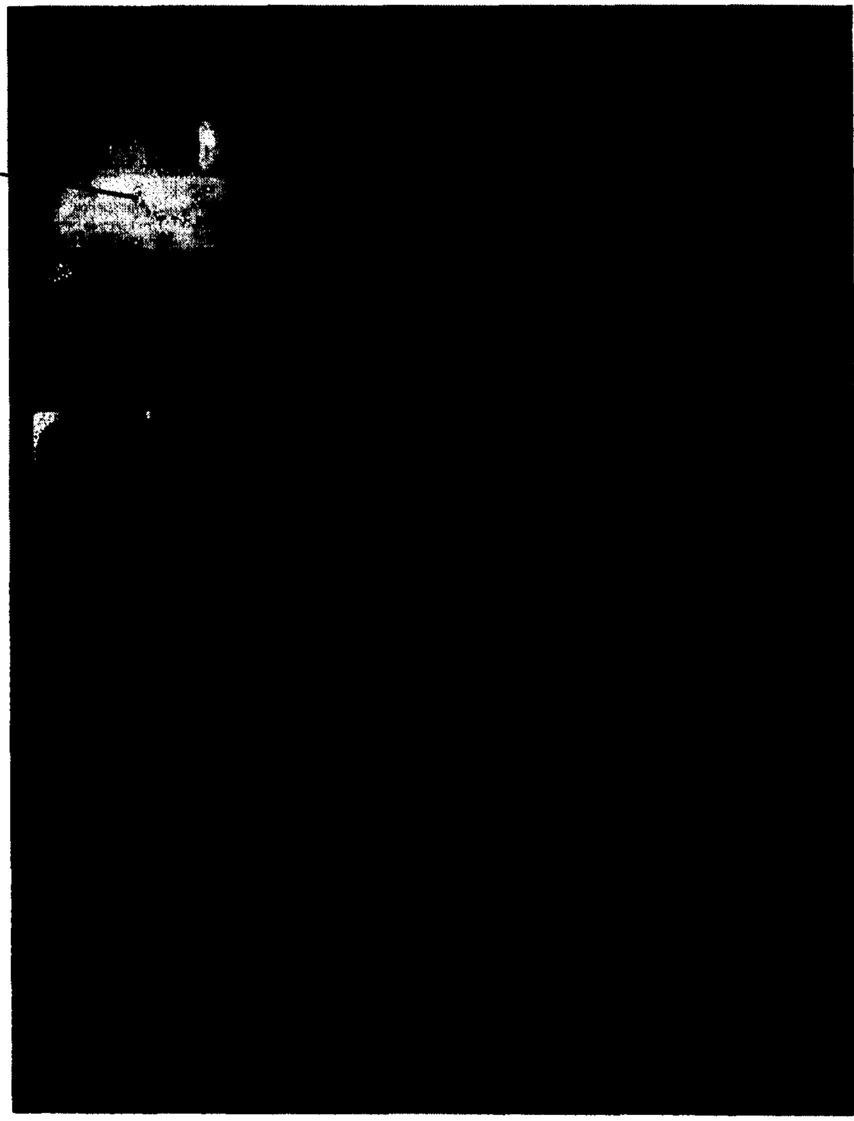
Location	Victim Distribution	Fire Location in the Unit
1st floor unit on fire	1 woman under a bed and 1 man lying under the kitchen's table	Fire occupies both kitchen and bathroom (through the wall)
2nd floor unit on fire	1 woman lying in front of living room sofa on the floor and 1 man under a table inside a bedroom	Fire occupies a bedroom across the bedroom with the man under the table
3rd floor unit on fire (2nd from staircase)	1 boy in the corner of the living room	Fire is in the living room right across the victim
3rd floor unit on fire (4th from staircase)	1 man coughing in the balcony, 1 woman under 2 beds, and 1 woman sitting in the bathtub	Fire occupies the bathroom next to the bedroom with woman under 2 beds

Please see Appendix K for the full mission plan instruction given to the participants. With the incomplete information condition in the apartment setting, participants are not told the number and locations of both fire and victims. In the mission plan, we instruct participants to start searching floor 1 before going to floor 2 and finally, floor 3. The surprise obstruction in this condition is that the stairway to go from the 1st to the 2nd floor is blocked by fire and the team must find another way to get to the two upper floors (2nd and 3rd). The solution is for the team to go back downstairs and exit the apartment from where they entered and find a ladder to the rooftop. Once they are at the rooftop, they must climb down the roof hatch (ladder already provided). Participants are not told beforehand that the ladder to the rooftop and the roof hatch ladders are present because we want the teams to explore alternative pathways on their own.

Apartment-Incomplete-1st floor unit on fire next to staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

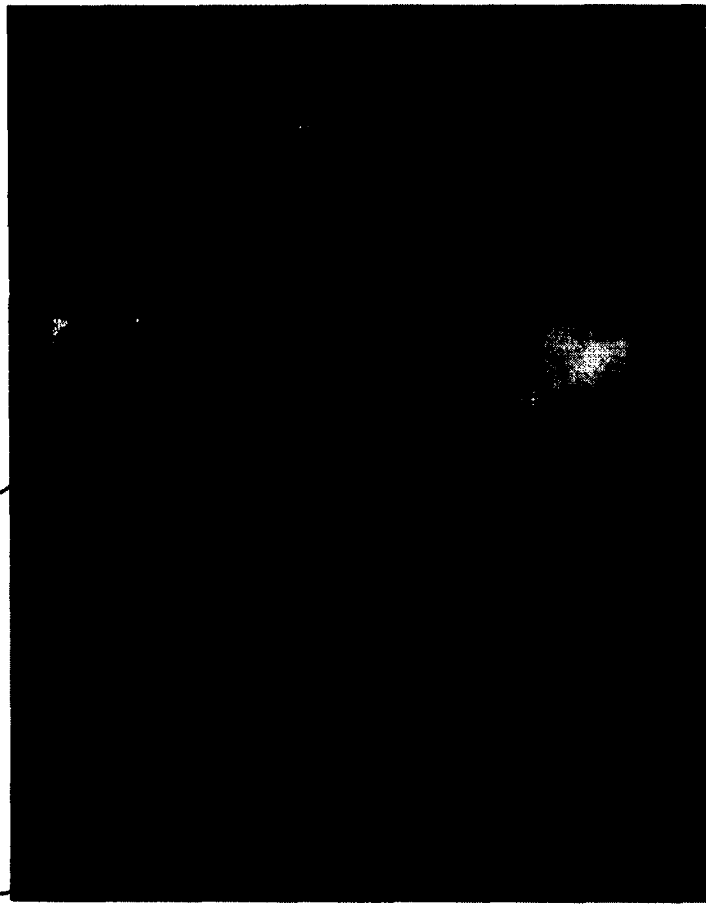


Apartment-Incomplete-2nd floor unit on fire 3rd from staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



Apartment-Incomplete-3rd floor unit on fire, 2nd from the staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

Apartment-Incomplete-3rd floor unit on fire, 4th from the staircase (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

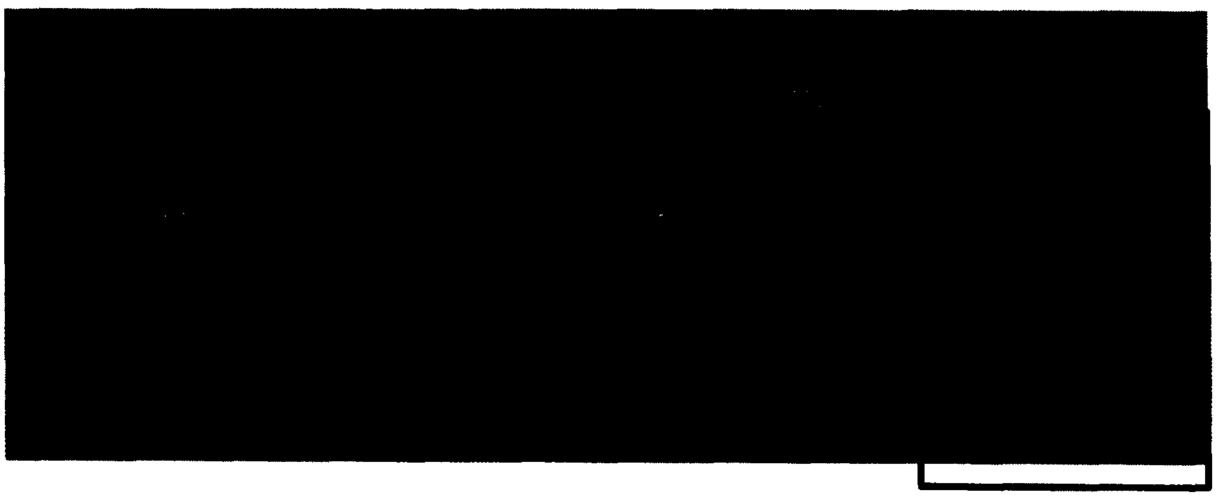


1 woman under 2 beds

Fire

1 woman sitting in bathtub

1 man coughing/holding throat in the balcony



Experimental Conditon: Office-Complete

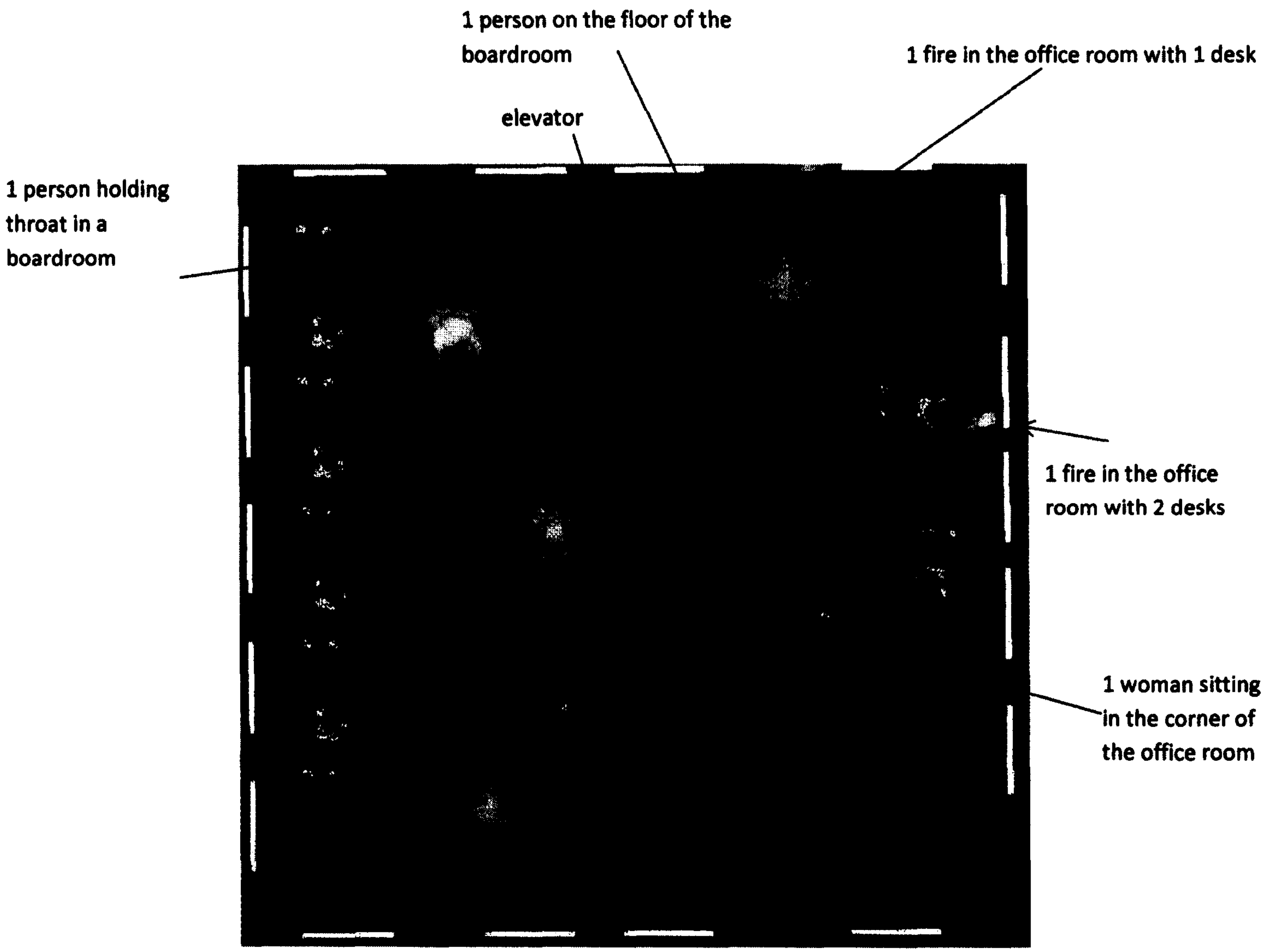
Location	# of fires	# of victims
Floor 4	2	4
Floor 5	3	2
Floor 3	1	2

Total Fires: 6
Total Victims: 8

Location	Victim Distribution	Fire Location in the Unit
Floor 4	2 people in the boardroom next to the office room with 1 desk, 1 woman in corner of the office room w/ 2 pairs of desks, and 1 person under the desk of the office room with 1 desk	1 fire at the office room with 1 desk and another at the neighboring office room with 2 pairs of desks
Floor 5	1 man underneath a table of the dining room that's closest to the window and 1woman in the electrical/cable room	Fire is in the boardroom next to the kitchen. 1 obstruction fire at doorways connecting the office room with 1 desk and another fire obstruction at the door to the left of the elevator (when facing the elevator's doors)
Floor 6	1 woman sitting in the ladies' bathroom and 1 man underneath cafeteria table that's the closest to the neighboring boardroom	Fire is in the men's bathroom

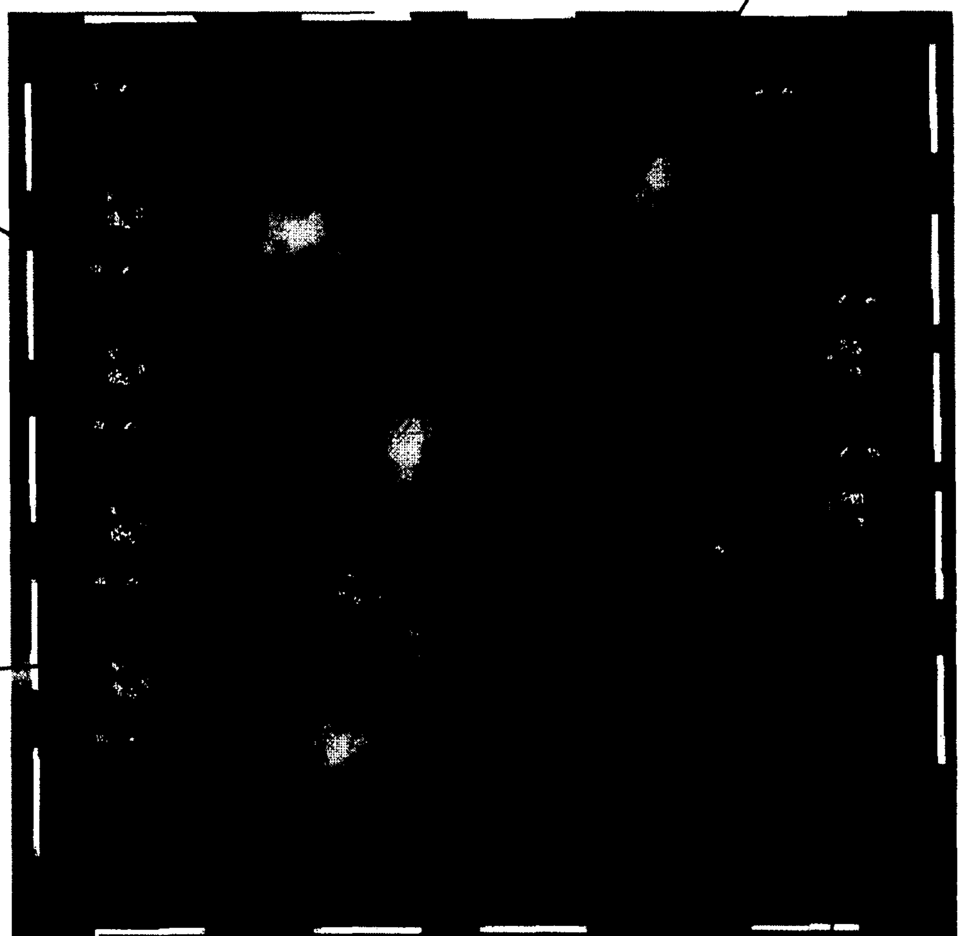
Please see Appendix K for the full mission plan instruction given to the participants. In this condition, we tell participants to search systematically from the fourth, to the fifth, and finally the sixth floor (there are only fires and victims on those three floors). The number of fire and victims and how they are distributed amongst the three floors are specified in the mission plan. They are not to proceed to the next upper floor unless they are sure they have found all fires and victims on the current floor. The two obstruction fires are placed on the fourth floor where they block one door by the elevator and two doorways that connect a boardroom and a neighboring office. Teams must cooperate to get around the two obstruction fires and search the entire first floors.

Office/Complete-Floor 4- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



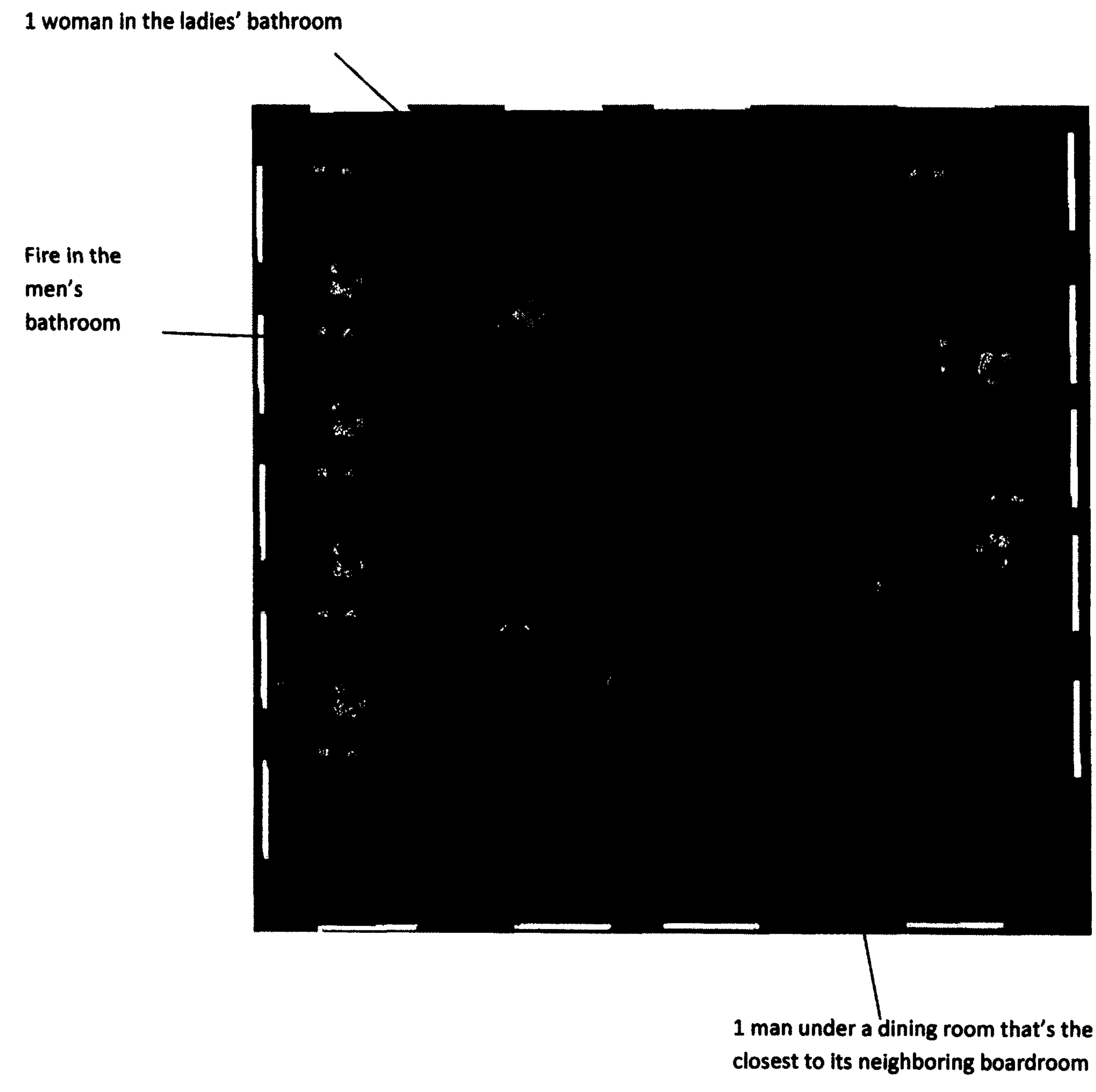
Note: Fires and victims unlabeled in this figure are those on floors 5 and 6. XVR allows the experimenter's central computer to have a cross-section, bird's eye view of the floors, but when the lower floors are viewed, the items (fire, victims, and smokes) placed on the upper floors do not disappear (there is no option to hide items being placed on upper floors when viewing the lower floors). Items on lower floors however, do not appear when viewing upper floors.

Office/Complete-Floor 5- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



Note: Fires and victims unlabeled in this figure are those on floor 6. XVR allows the experimenter's central computer to have a cross-section, bird's eye view of the floors, but when the lower floors are viewed, the items (fire, victims, and smokes) placed on the upper floors do not disappear (there is no option to hide items being placed on upper floors when viewing the lower floors). Items on lower floors however, do not appear when viewing upper floors.

Office/Complete-Floor 6- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



Experimental Conditon: Office-Incomplete

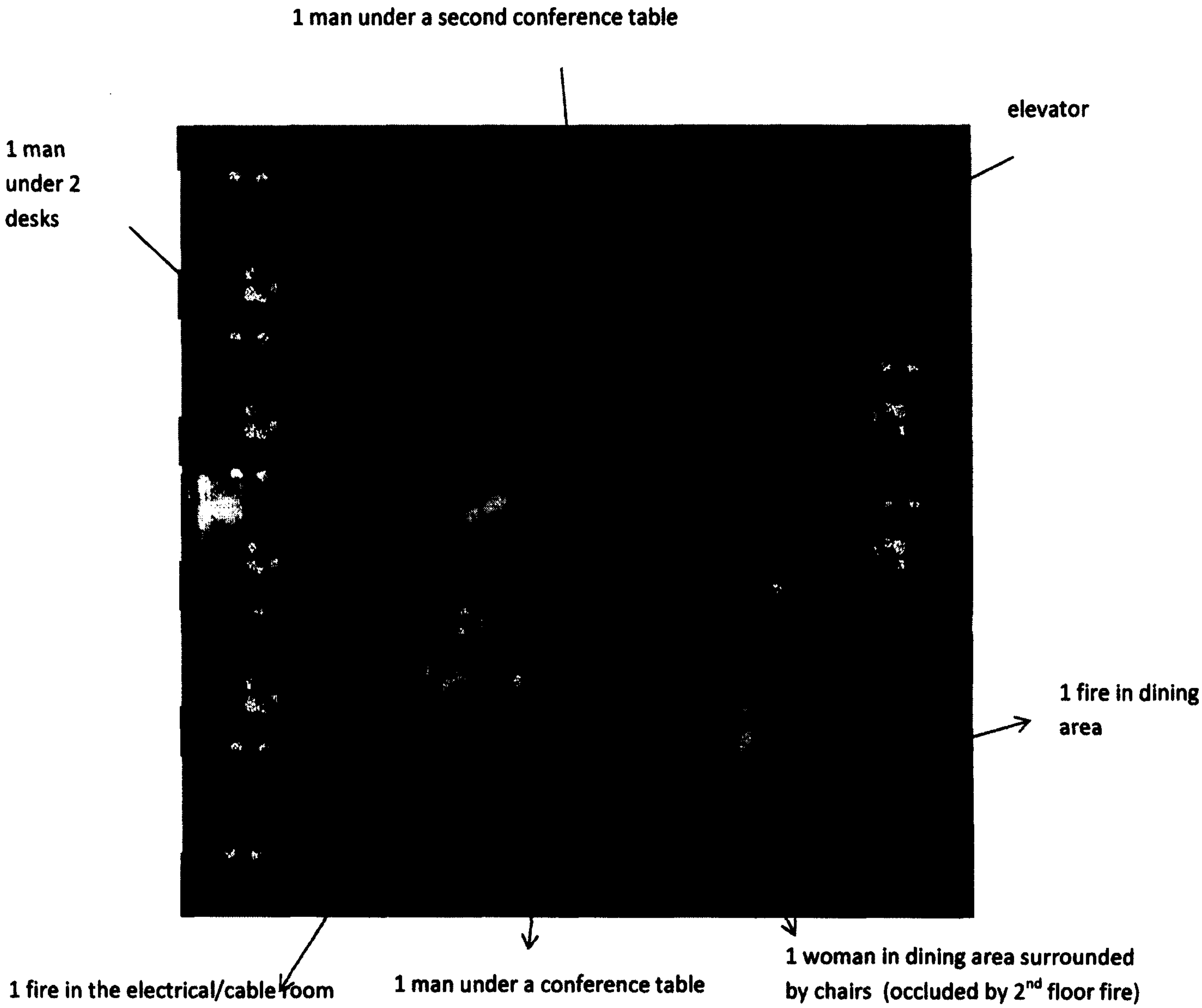
Location	# of fires	# of victims
Floor 1	2	4
Floor 2	3	2
Floor 3	1	2

Total Fires: 6
Total Victims: 8

Location	Victim Distribution	Fire Location in the Unit
Floor 1	1 woman in the dining area surrounded by chairs; 1 man under the table of boardroom next to dining area; 1 man under the table of a second boardroom; 1 man under 2 desks in the northeast corner of the office	1 fire in an electrical/cable room; 1 fire at the door to the left of elevator (when facing the elevator's doors)
Floor 2	1 woman underneath middle table of dining area and 1 man under 2 desks to the left of the fire when facing the windows	Fire is at the open area with six pairs of desks (the 2 central desks) by the bathrooms. 1 fire in the boardroom next to dining area and 1 fire in dining area doorway (obstructions)
Floor 3	1 man behind the door in the room where the fire is and 1 woman lying on the floor under 2 desks in the neighboring office room with 2 desks	Fire is at an office room with 1 desk

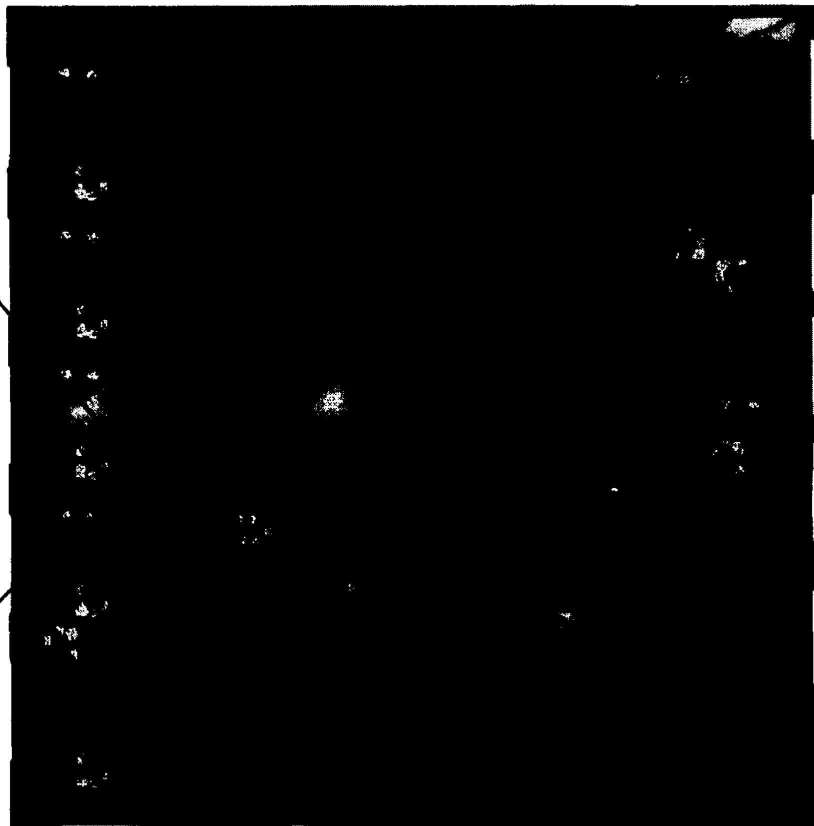
Please see Appendix K for the full mission plan instruction given to the participants. In this condition, we tell participants to search systematically from the first, to the second, and finally the third floor (fire and victims are placed on those three floors only). They are not to proceed to the next upper floor unless they are sure they have found all fires and victims on the current floor. We do not inform participants of the number and location of fires and victims on the three floors. The two obstruction fires are placed on the first floor where they block one door by the elevator and two doorways that connect a boardroom and the dining area. Teams must cooperate to get around the two obstruction fires and search the entire first floors.

Office/Incomplete-Floor 1- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



Note: Fires and victims unlabeled in this figure are those on floors 2 and 3. XVR allows the experimenter's central computer to have a cross-section, bird's eye view of the floors, but when the lower floors are viewed, the items (fire, victims, and smokes) placed on the upper floors do not disappear (there is no option to hide items being placed on upper floors when viewing the lower floors). Items on lower floors however, do not appear when viewing upper floors.

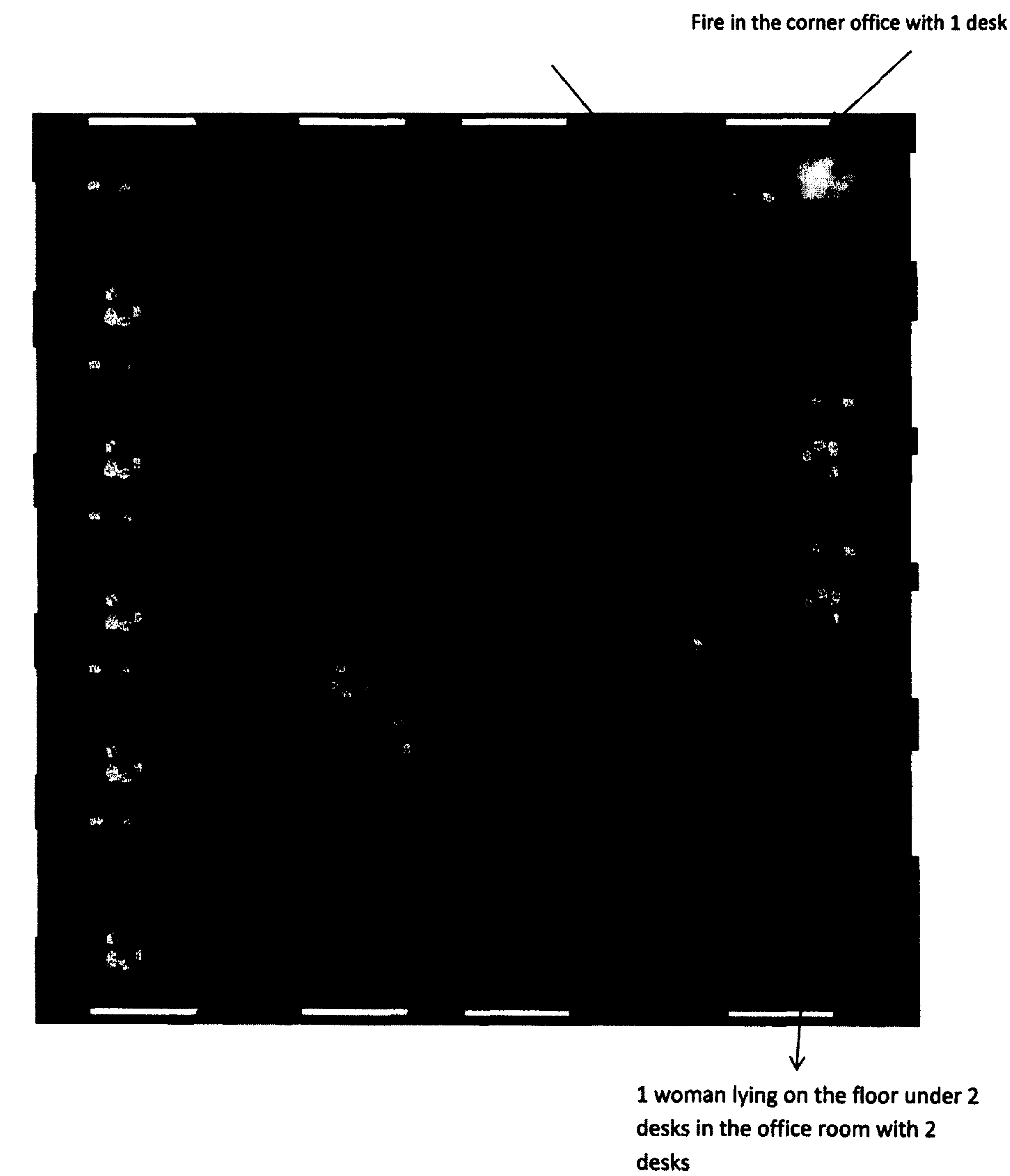
Office/Incomplete-Floor 2- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)



Note: Fires and victims unlabeled in this figure are those on floor 3. XVR allows the experimenter's central computer to have a cross-section, bird's eye view of the floors, but when the lower floors are viewed, the items (fire, victims, and smokes) placed on the upper floors do not disappear (there is no option to hide items being placed on upper floors when viewing the lower floors). Items on lower floors however, do not appear when viewing upper floors.

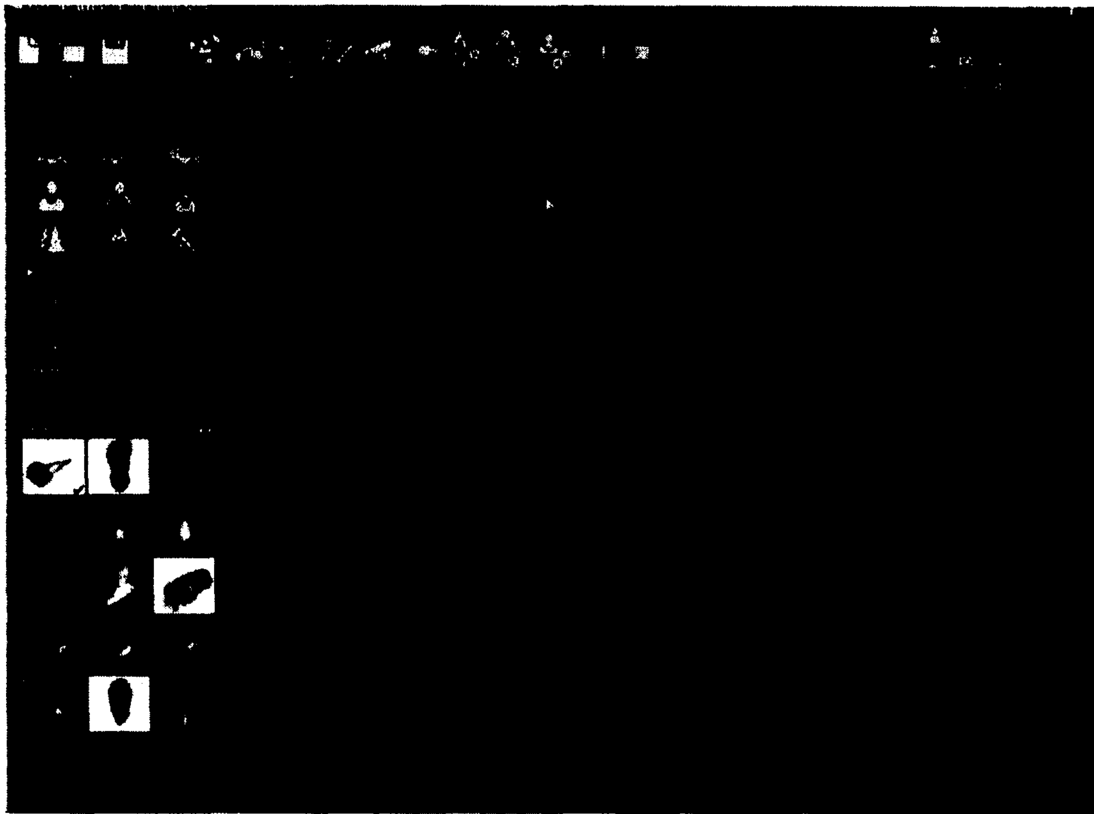
Office/Incomplete-Floor 3- (from experimenter's central computer-bird's eye view-NOT SEEN BY THE PARTICIPANTS)

1 man under the corner office with 1 desk


Fire in the corner office with 1 desk
1 woman lying on the floor under 2 desks in the office room with 2 desks

Appendix C - Bird's Eye View of Avatars

The Bird's Eye View of the Participants' Avatars from the Experimenter's Computer



Firefighter Avatar of Participant A

Firefighter Avatar of Participant B

Appendix D – Demographic Questionnaire

Please fill in or put a check mark next to the appropriate answer

BACKGROUND INFORMATION

What is your sex?
[ ] Male
[ ] Female

What is your age?

What is your first language?
[ ] English
[ ] French
[ ] Other (please specify)______________

You are working with a teammate in this study. How well do you know your teammate?
[ ] I have never met this person before
[ ] I have met this person, but not very well acquainted
[ ] I am well acquainted with this person

EXPERIENCE WITH TECHNOLOGY

How often do you use a computer?
[ ] Several times a day
[ ] Once a day
[ ] Several times a week
[ ] Once a week
[ ] Once/twice a month
[ ] Every few months
[ ] Once/twice a year
[ ] Never

How often do you play video games on a computer?
[ ] Several times a day
[ ] Once a day
[ ] Several times a week
[ ] Once a week
[ ] Once/twice a month
[ ] Every few months
[ ] Once/twice a year
[ ] Never

How often do you play video games on a joystick?
[ ] Several times a day
[ ] Once a day
[ ] Several times a week
[ ] Once a week
[ ] Once/twice a month
[ ] Every few months
[ ] Once/twice a year
[ ] Never

How often do you play strategy games (computer/cellphone/with a gaming system on your TV at home)?
[ ] Several times a day
[ ] Once a day
[ ] Several times a week
[ ] Once a week
[ ] Once/twice a month
[ ] Every few months
[ ] Once/twice a year
[ ] Never

How often do you play first-person shooter games (computer/cellphone/with a gaming system on your TV at home)?
[ ] Several times a day
[ ] Once a day
[ ] Several times a week
[ ] Once a week
[ ] Once/twice a month
[ ] Every few months
[ ] Once/twice a year
[ ] Never

Are you typically prone to cyber-sickness (headache/dizziness/nausea/vision blurriness when using computer/playing video games)?
[ ] Yes
[ ] Sometimes
[ ] No

Appendix E - SA Probe/Workload Rating Format

Sample Format of SA Probe Per Simulation Pause

AI1.L3.1 Your team will find all fire and victims and exit the building on time	[ ]True [ ]False	Confidence level [ ]Very high [ ]High [ ]Moderate [ ]Low [ ]Very Low

Please indicate your current level of perceived workload below by circling the appropriate number:

0	10	20	30	40	50	60	70	80	90	100
No perceived workload										Extremely high workload

Please estimate your teammate's current level of perceived workload below by circling the appropriate number:

0	10	20	30	40	50	60	70	80	90	100
No perceived workload										Extremely high workload

Note: Each time that simulation is paused, each participant will ALWAYS be given <u>ONE</u> QUASA questionnaire sheet in the format presented above. Both teammates will have the EXACT SAME questions every pause and will always be asked to indicate their current level of perceived workload and an estimate of their teammate's level of perceived workload (i.e., the bottom two boxes will always be present in every questionnaire sheet for every pause). The only item that will differ is the part highlighted in yellow (highlighted for the purpose of this prospectus only) which is the situation awareness statement, that they must indicate to be true or false and their level of confidence in their true/false response, because the question is randomly picked for every pause. Please see the next appendix for the full list of the situation awareness questions.

Appendix F - List of SA Probe Statements

SA Statement Bank for Apartment-Incomplete Condition Pause 1 (1 will be randomly picked):

- Your team will find all fire and victims and exit the building on time
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- 1 victim is dangerously closer to the fire than other victims in this unit
- The victim in the kitchen is much closer to the fire than the victim in one of the bedrooms
- The victim in one of the bedrooms is much closer to the fire than the victim in the kitchen
- None of the victims in this unit is in the same room as the fire
- Fire in this unit occupies more than 1 room
- There are two victims in this unit
- There is only 1 victim in this unit
- Your teammate is in the same room/area as you are
- Your teammate has found a victim or a fire in this unit
- A fire or a victim has been detected

SA Statement Bank for Apartment-Incomplete Condition Pause 2 (1 will be randomly picked)

- You will find all victims and fire, but not exit the building on time
- Your team will exit the building on time
- You will successfully find all fire and victims
- The unit your team just searched is right next to the staircase
- The unit your team just searched is second from the staircase
- The unit your team just searched is third from the staircase
- So far, there are 2 victims in 1 unit
- So far, there are 3 victims in 1 unit
- So far, there are 2 fires across 2 units

SA Statement Bank for Apartment-Incomplete Condition Pause 3 (1 will be randomly picked):

- Your team will find all fire and victims and exit the building on time
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- 1 victim is dangerously closer to the fire than other victims in this unit
- The victim in one of the bathrooms is much closer to the fire than the victim in the living room
- The victim in one of the bedrooms is much closer to the fire than the victim in the kitchen
- None of the victims in this unit is in the same room as the fire
- Fire in this unit occupies more than 1 room

- There are two victims in this unit
- There is only 1 victim in this unit
- Your teammate is in the same room/area as you are
- Your teammate has just found a fire or a victim
- A fire or a victim has been detected

SA Statement Bank for Apartment-complete Condition Pause 1 (1 will be randomly picked):

- Your team will find all fire and victims and exit the building on time
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- 1 victim is dangerously closer to the fire than other victims in this unit
- The victim in the kitchen is much closer to the fire than the victim in one of the bedrooms
- The victim in one of the bedrooms is much closer to the fire than the victim in the kitchen
- None of the victims in this unit is in the same room as the fire
- Fire in this unit occupies more than 1 room
- There are two victims in this unit
- There is only 1 victim in this unit
- Your teammate is in the same room as you are
- Your teammate has found a victim or a fire in this unit
- A fire or a victim has been detected

SA Statement Bank for Apartment-complete Condition Pause 2 (1 will be randomly picked)

- You will find all victims and fire, but not exit the building on time
- Your team will exit the building on time
- You will successfully find all fire and victims
- The unit your team just searched is right next to the staircase
- The unit your team just searched is second from the staircase
- The unit your team just searched is third from the staircase
- So far, there are 2 victims in 1 unit
- So far, there are 3 victims in 1 unit
- So far, there are 2 fires across 2 units

SA Statement Bank for Apartment-complete Condition Pause 3 (1 will be randomly picked):

1. Your team will find all fire and victims and exit the building on time
2. Your team will exit the building on time
3. Your team will not exit the building on time
4. Your team will find all fire and victims
5. Your team will not find all fire and victims
6. 1 victim is closer to the fire than other victims in this unit
7. The victim in the kitchen is much closer to the fire than the victim in one of the bedrooms

8. The victim in one of the bathrooms is much closer to the fire than the victim in the living room
9. None of the victims in this unit is in the same room as the fire
10. Fire in this unit occupies more than 1 room
11. There are two victims in this unit
12. There is only 1 victim in this unit
13. Your teammate is in the same room as you are
14. Your teammate has found a victim or a fire in this unit
15. A fire or a victim has been detected

SA Statement Bank for Office-Incomplete Condition Pause 1 (1 will be randomly picked):

- Your team will find all fires and victims on this floor
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- None of the victims on this floor are in the same room(s) as the fire(s)
- All except 1 victim on this floor are dangerously closer to the fire
- One fire on this floor is not endangering any victims in its immediate surrounding
- All fire on this floor endangers all victims in its immediate surrounding
- Only 1 fire is not in the same room as some of the victims
- You and your teammate are in the same room/area
- Your teammate has found a fire or a victim
- There are 2 victims on this floor
- There are 2 fires on this floor
- There are 3 victims on this floor

SA Statement Bank for Office-Incomplete Condition Pause 2(1 will be randomly picked):

- Your team will find all fires and victims
- Your team will find not find all fires and victims
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team has found that there are 2 fires that are very close to the elevator on this floor
- Your team has found 1 fire that is very close to the staircase so far on this floor
- Your team has found 2 fires that are very close to the staircase so far on this floor
- Your team has discovered that there is at least 1 fire that occupies 1 room only ON THIS FLOOR thus far
- So far, your team has detected 1 fire on THIS floor
- So far, your team has detected 2 fires on this floor
- So far, your team has detected 2 victims on this floor
- So far, your team has detected 1 victim on this floor

SA Statement Bank for Office-Incomplete Condition Pause 3 (1 will be randomly picked):

- Your team will find all fire and victims and exit the building in time
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- All of the victims on this floor are about equally close to the fire
- One fire on this floor is not endangering any victims in its immediate surrounding (fire is not in the same region of the floor/room as the victims)
- The fire on this floor is farther from the bathroom compared to any of the fires on the previous floor
- The fire on this floor is farther from the bathroom compared to any of the fires on the previous floor
- The fire on this floor is farther from the staircase compared to any of the fires on the previous floor
- There are 4 fires on this floor
- You and your teammate are in the same room/area
- Your teammate has found a fire or a victim on this floor
- There are 2 victims on this floor
- There is 1 fire on this floor

SA Statement Bank for Office-Complete Condition Pause 1 (1 will be randomly picked):

- Your team will find all fires and victims on this floor
- Your team will exit the building on time
- Your team will not exit the building in time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- All of the victims on this floor are about equally close to the fire
- There are multiple rooms with multiple victims in it
- One fire on this floor is not endangering any victims in its immediate surrounding
- All fire on this floor endangers all victims in its immediate surrounding
- Only 1 fire is not in the same room as some of the victims
- There are 4 fires on this floor
- You and your teammate are in the same room
- Your teammate has found a fire or a victim
- There are 2 victims on this floor
- There are 2 fires on this floor

SA Statement Bank for Office-complete Condition Pause 2 (1 will be randomly picked):

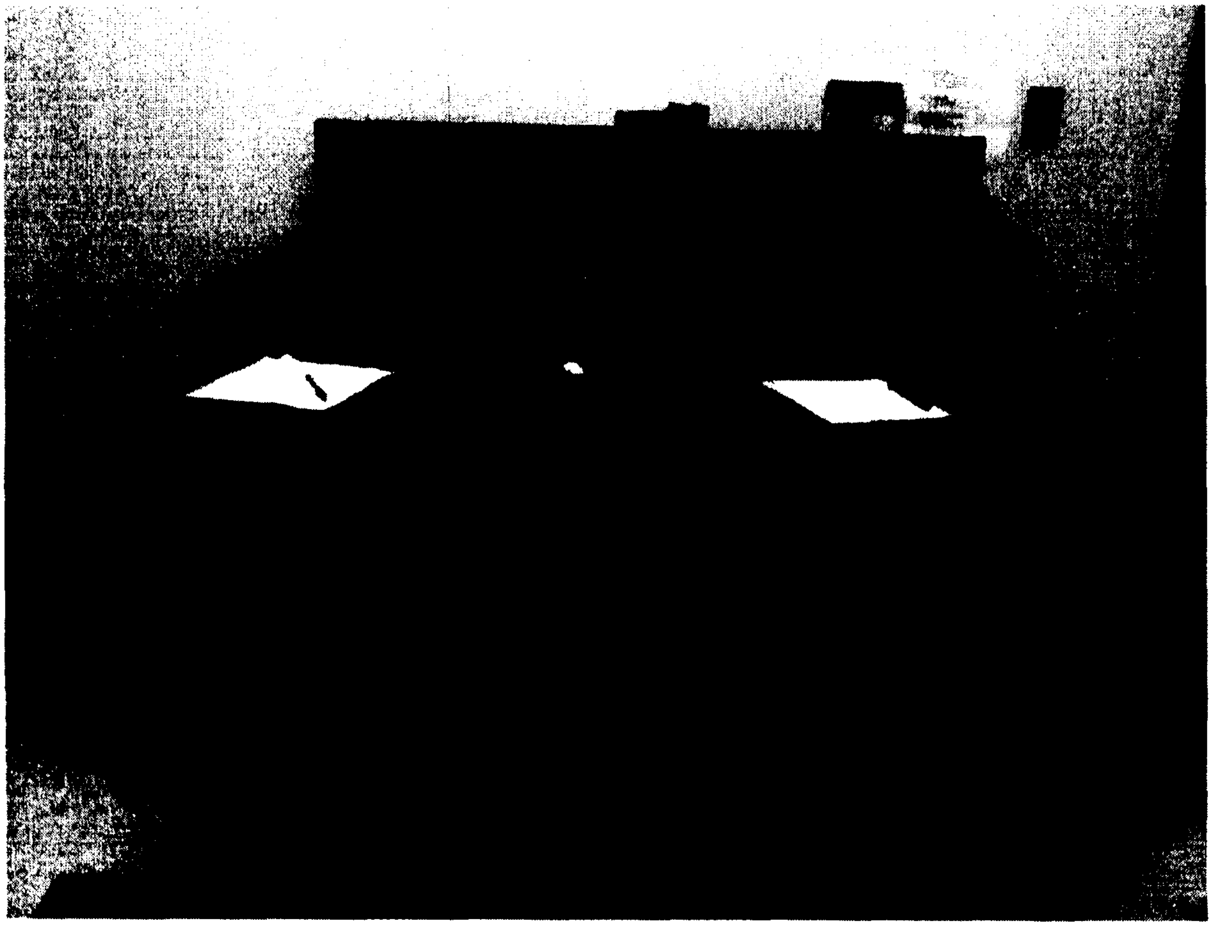
- Your team will find all fires and victims on this floor
- Your team will find not find all fires and victims
- Your team will exit the building on time

- Your team will not exit the building on time
- Your team has found that there are 2 fires that are very close to the elevator
- Your team has found 1 fire that is very close to the staircase so far
- Your team has found 2 fires that are very close to the staircase so far
- Your team has discovered that there is at least 1 fire that occupies 1 room only ON THIS FLOOR thus far
- So far, your team has detected 1 fire on THIS floor
- So far, your team has detected 2 fires on this floor
- So far, your team has detected all victims on this floor
- So far, your team has detected 1 victim on this floor

SA Statement Bank for Office-complete Condition Pause 3 (1 will be randomly picked):

- Your team will find all fire and victims and exit the building on time
- Your team will exit the building on time
- Your team will not exit the building on time
- Your team will find all fire and victims
- Your team will not find all fire and victims
- None of the victims on this floor are in the same room(s) as the fire(s)
- All except 1 victim on this floor are dangerously much closer to the fire
- One fire on this floor is not endangering any victims in its immediate surrounding (fire is not in the same region of the floor/room as the victims)
- The fire on this floor is farther from the bathroom compared to any of the fires on the previous floor
- At least 1 victim is not in the same room as the fire
- There is 1 fire on this floor
- You and your teammate are currently in the same room/area on this floor
- Your teammate has found a fire or a victim on this floor
- There are 2 victims on this floor
- There are 2 fires on this floor

Appendix G - Physical Layout of Experimental Set-up



Appendix H – Counterbalanced Order of Scenario Presentation

	First Scenario	Second Scenario	Third Scenario	Fourth Scenario
Counterbalance 1	Apartment-Incomplete information	Apartment-Complete information	Office-Incomplete information	Office-Complete information
Counterbalance 2	Apartment-Complete information	Apartment-Incomplete information	Office-Complete information	Office-Incomplete information
Counterbalance 3	Office-Incomplete information	Office-Complete information	Apartment-Incomplete information	Apartment-Complete information
Counterbalance 4	Office-Complete information	Office-Incomplete information	Apartment-Complete information	Apartment-Incomplete information
Counterbalance 5	Apartment-Incomplete information	Apartment-Complete information	Office-Complete information	Office-Incomplete information
Counterbalance 6	Apartment-Complete information	Apartment-Incomplete information	Office-Incomplete information	Office-Complete information
Counterbalance 7	Office-Incomplete information	Office-Complete information	Apartment-Complete information	Apartment-Incomplete information
Counterbalance 8	Office-Complete information	Office-Incomplete information	Apartment-Incomplete information	Apartment-Complete information

Appendix I - Training Slides Version 1

Powerpoint Slides Version 1 (when doing apartment scenarios first)

SOFTWARE TRAINING

At the start of the training and *all* experimental scenarios, you will each find yourself inside a car separate from your teammate.

If you see no car in front of you, that means your teammate's car is behind you and you need to drive forward first.

If you see your teammate's car in front of you, please wait until your teammate starts driving and simply follow behind him/her.

For driving instructions, please refer to the next slide

Driving Instructions

- To drive forward, simply move the stick forward OR press the forward arrow key
- If at first the car won't move forward, try left-clicking your mouse
- To stop the car, simply pull back the stick to its original default position OR cease pressing the forward arrow key (keyboard)
- To exit the car, press the firing button or press "Enter" on keyboard

Driving Instructions Con't

- For this training session, if you drive at the front, please stop and exit the car when instructed by the experimenter
- If you drive behind a teammate, simply stop behind him/her and exit the car

Navigating the Virtual Environment

Joystick Manoeuvres Practice

Please practice the following manoeuvres based on information from the previous slide:

1. Walk forward
2. Walk backward
3. Turn left
4. Turn right
5. Adjust speed control to try out different walking speeds

Joystick Features (No Keyboard Alternatives)

Joystick Manoeuvres Practice

Please practice the following manoeuvres based on the previous slide's information:

1. Tilt your head up
2. Tilt your head down
3. Turn your head to the left
4. Turn your head to the right
5. Move sideways to the left
6. Move sideways to the right
7. Move the stick (to walk forward, backward, turn left, and right) while pressing the sideway buttons.
8. Kneel down

In the following training sessions, please do not explore/roam around the surrounding environment UNLESS instructed by the experimenter

- Please walk towards the door highlighted in red oval and enter it.
- You and your teammate will take turns to practise opening and closing the first door to your left

[redacted]

Opening Doors

- To open a door with joystick, approach it until the colour of door turns purple, and hit the firing button.
- To close a door, approach until it turns purple and hit the firing button
- To use keyboard, approach the opened/closed door with forward arrow key and press "Enter" when it turns purple

After you and your teammate is finished practising with the door, please follow the experimenter's instruction for the next training

[redacted]

Staircase: Apartment

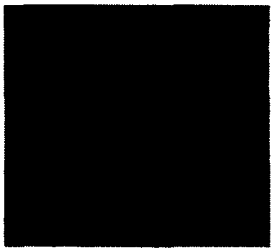
- To walk up or down the stairs with joystick, move it forward until you reach the top or bottom of staircase
- To use keyboard, use the forward arrow key
- Tips: If you wish, you may tilt your head up when going upstairs and down when going downstairs
- Please practise going up to the next floor and back down with your teammate (one person walking behind the other)

When you and your teammate are finished practising with the staircase, exit the door that you entered from, and turn left around the corner where you will see two adjacent ladders resting on two balconies. Both of you should take one ladder and follow instructions on the next slide

[redacted]

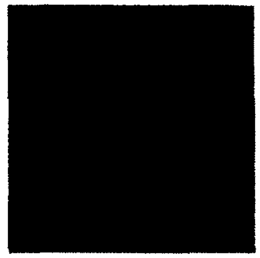
Climbing Ladders

- To climb a ladder with joystick, push the joystick forward and towards the ladder until you reach the top of the structure.
- To use keyboard, move forward with forward arrow button until you reach the top of the structure
- Tips: If you wish, you may tilt your head up as you climb up



Descending Ladders

- To climb down a ladder with joystick, turn your avatar's head down and walk forward normally towards the ladder until you reach the ground.
- To use keyboard, press the forward arrow key until you reach the ground
- Tips: If you wish, you may tilt your head downward as you climb down the ladder



After climbing down the ladder, each of you will turn right around the corner of the apartment where you will see another ladder rested against the apartment's wall. Climb this ladder to the top of the roof

Going Down the Roof Hatch

- To go down the roof hatch, face the roof hatch with the view in the photo in the right
- Move joystick forward towards the roof hatch and face the ladder as you descend on it

Climb Up the Roof Hatch

- To climb up a roof hatch, move joystick forward towards the ladder
- Keep going until you reach the top of the ladder and your avatar will naturally jump onto the roof
- *Be careful not to get too close to the edge of the roof. You will fall and have to climb back up again!*
- Tips: If you wish, you may tilt your head up as you climb up

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Locating Victims

- In this study, you will be asked to locate victims. When you find a victim, you MUST approach him/her, jump twice (press spacebar twice), and say, , "Victim located". If you do not jump twice and say, "Victim located", it will be regarded as if you have NOT found a victim, even if you notice them. <u>Victims won't disappear after you locate them.</u>

Please practice with your teammate to approach, jump twice close the three victims you encounter on the rooftop, and say "Victim located."

18

Locating Fire

- In this experiment, an equally important goal is to locate the fire. When you have found a fire, you will indicate that you have found it by approaching the fire until you are just about to touch it, jump twice (press spacebar twice) and you will say, "Fire located." If you do not follow this specific procedure, it will be regarded as if you did not find the fire at all even though you notice it. <u>Fires won't disappear after you locate them</u>
- Do NOT cross the fire, but you may walk around it (If there is enough space).
- *To practise locating fire, each of you are to approach the two fires behind the victims, jump twice, and say, "Fire located."*

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Appendix J – Training Slides Version 2

PowerPoint Training Slides Version 2 (when doing office scenarios first)

SOFTWARE TRAINING

At the start of the training and ***all*** experimental scenarios, you will each find yourself inside a car separate from your teammate.

If you see no car in front of you, that means your teammate's car is behind you and you need to drive forward first.

If you see your teammate's car in front of you, please wait until your teammate starts driving and simply follow behind him/her.

For driving instructions, please refer to the next slide

Driving Instructions

- To drive forward, simply move the stick forward or press the forward arrow key
- If at first the car won't move forward, try left-clicking your mouse
- To stop the car, simply pull back the stick to its original default position OR cease pressing the forward arrow key (keyboard)
- To exit the car, press the firing button or press "Enter" on keyboard

Driving Instructions Con't

- For this training session, if you drive at the front, please stop and exit the car when instructed by the experimenter
- If you drive behind a teammate, simply stop behind him/her and exit the car
- *Note: should you need to back up, simply move the joystick backward*

Navigating the Virtual Environment

Joystick Manoeuvres Practice

Please practice the following manoeuvres based on the information from the previous slide:

1. Walk forward
2. Walk backward
3. Turn left
4. Turn right
5. Adjust speed control to try out different walking speeds

Joystick Features (No Keyboard Alternatives)

Joystick Manoeuvres Practice

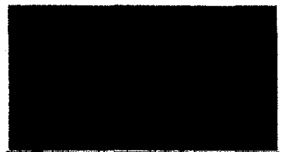
Please practice the following manoeuvres based on the previous slide's information:

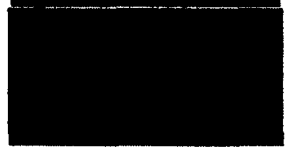
1. Tilt your head up
2. Tilt your head down
3. Turn your head to the left
4. Turn your head to the right
5. Move sideways to the left
6. Move sideways to the right
7. Move the stick (to walk forward, backward, turn left, and right) while pressing the sideway buttons.
8. Kneel down

<u>In the following training sessions, please do not explore/roam around the surrounding environment UNLESS instructed by the experimenter</u>

Opening/Closing Doors: Office

- Move joystick forward to walk towards the door as you tilt your head downward towards the doorknobs/handles
- Wait until it turns purple and hit the firing button
- To use keyboard, wait until the door turns purple before you press "Enter" to open it
- When you enter the lobby, walk to the door straight ahead and open it with the same procedure as described above





10

Staircase: Office

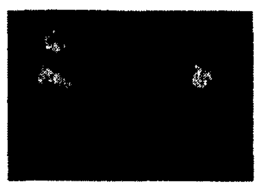
- To walk up or down the stairs with joystick, move it forward until you reach the top or bottom of staircase
- To use keyboard, use the forward arrow key
- Tips: If you wish, you may tilt your head up when going upstairs and down when going downstairs
- Please practice going down to the next floor and back up again with your teammate

Next, please follow the experimenter's instruction to exit the building

Locating Victims

In this study, you will be asked to locate victims. When you find a victim, you MUST approach him/her, jump twice (press spacebar twice), and say "Victim located". If you do not jump, it will be regarded as if you have NOT found a victim, even if the victim is in your line of sight. <u>Fires won't disappear after you locate them</u>

Please practice with your teammate to approach and jump close to the three victims you encounter outside the office building



11

Locating Fire

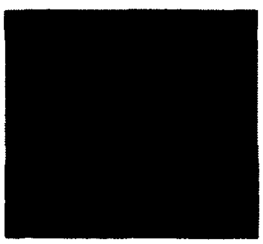
- In this experiment, an equally important goal is to locate the fire. When you have found a fire, you will indicate that you have found it by approaching the fire until you are just about to touch it, jump twice (press spacebar twice) and you will say, "Fire located." If you do not follow this specific procedure, it will be regarded as if you did not find the fire at all even though you notice it. Fires won't disappear after you locate them
- Do NOT cross the fire, but you may walk around it (if there is enough space).
- *To practise locating fire, each of you are to approach the two fires behind the victims and then say, "Fire located."*

Apartment Building Training

- In the apartment building, use the same procedure that you employed in the office building to open/close doors, but you do **not** need to tilt your head down.
- Walk up and down the stairs the same way that you did in the office building

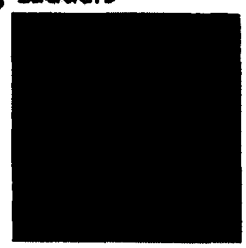
Climbing Ladders

- To climb a ladder with joystick, push the joystick forward and towards the ladder until you reach the top of the structure.
- To use keyboard, move forward with forward arrow button until you reach the top of the structure
- Tips: If you wish, you may tilt your head up as you climb up



Descending Ladders

- To climb down a ladder with joystick, turn your avatar's head down and walk forward normally towards the ladder until you reach the ground.
- To use keyboard, press the forward arrow key until you reach the ground
- Tips: If you wish, you may tilt your head downward as you climb down the ladder

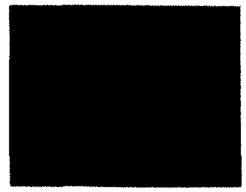


After climbing down the ladder, turn right around the corner of the apartment where you will see another ladder rested against the apartment's wall. Climb this ladder to the top of the roof

17

Going Down the Roof Hatch

- To go down the roof hatch, face the roof hatch with the view in the photo in the right
- Move joystick forward towards the roof hatch and face the ladder as you descend on it
- Tips: You may tilt your head downward as you go down the roof hatch on the ladder



18

Climb Up the Roof Hatch

- To climb up a roof hatch, move joystick forward towards the ladder
- Keep going until you reach the top of the ladder and your avatar will naturally jump onto the roof
- *Be careful not to get too close to the edge of the roof. You will fall and have to climb back up again!*
- Tips: If you wish, you may tilt your head up as you climb up

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Appendix K – Mission Instruction

Firefighting Simulation Study

In this experiment, you and your teammate will play the roles of two firefighters in a firefighting mission. Your two goals in this experiment are to **locate all victims and fires as fast as you can in 10 minutes! Missing any one fire or victim is considered a form of failure.**

You may tilt/adjust your screens at any time for a comfortable view of the monitor.

Emergency Call 1
Information from Dispatch Center:
We have received a fire emergency call about a fire in a four-storey apartment building and the following information:
-There are 8 victims spread across 4 apartments

Location	# of fires	# of victims
3rd floor apartment unit (1st unit searched)	1	2
2nd floor apartment unit (3rd unit from staircase)	1	1
1st floor apartment unit (2nd unit from staircase)	1	2
1st floor apartment unit (4th unit from staircase)	1	3

Mission Plan (You may refer back to these instructions during your mission):

- You will first search the apartment that has a ladder rested against the balcony of a 3rd floor apartment unit on fire (you will see the ladder). When finished with the 3rd floor apartment unit, go downstairs to the 2nd floor. The second floor apartment unit on fire is third on the right hand side after you've arrived from the stairs. Afterwards, descend to the first floor, where there are 2 apartment units on fire: search the 2nd unit from the staircase before you go to the 4th unit from the staircase on the 1st floor.
- Search THOROUGHLY inside the apartment units(corners, around furniture, every nook and cranny possible)
- You and your teammate must always stay together at all times, but you are encouraged to split up inside the same apartment unit to expedite the search (i.e., BOTH OF YOU must be present in the same apartment unit, but may separate within that SAME apartment when searching)
- When you have found a fire, approach close enough without crossing or walking into it, jump twice (press spacebar 2X) then say, "Fire located" to report what you've found and where to your teammate. Resume your search IMMEDIATELY afterwards. If you do not

jump TWICE and say "Fire located," it will be regarded as if you HAVE NOT FOUND the fire at all, even if you notice them.

- When you have found a victim, approach him/her, say "Victim located," jump twice (press spacebar 2X), report to your teammate where the person is, and resume your search IMMEDIATELY afterwards. If there is any furniture or if the victim is too close to the fire, stand & jump at the safest, closest distance possible. If you do not jump TWICE and say "Victim located," it will be regarded as if you HAVE NOT FOUND the victims at all, even if you notice them.
- If you think your teammate has found the same fire or victim that you have previously encountered, communicate this to him or her. If you have found the same fire or victim that you think your teammate has previously encountered, communicate this information to him or her
- You do not need to see your teammate's reported findings and vice versa
- Ignore flames licking the ceilings or the floors
- You have 10 minutes from the moment you enter the premise to finish this mission
- **Under NO circumstances should your team deviate from this plan.**
- **Unless you feel any discomforts, you must NOT give up on the mission under ANY circumstances**
- Each of you will be inside of a car separate from your teammate at the beginning of the scenario. Please drive straight and park behind the large fire with the tall black smoke (this fire is just a landmark and **not** part of your mission)
- Before you enter the premise, please wear a safety breathing mask by pressing the button numbered "8" on the base of the joystick

Emergency Call 2

Information from Dispatch Centre: We have received a fire emergency call about a fire in a four-storey apartment building and the following information:

- There are victims in apartment units located on floor 1, 2, and 3, but the number of victims and exact locations are unknown. Note: the floor you will first enter from outside is the ground floor. You must take the staircase to floor 1.
- We know there are multiple fires, but we do not know how many or where
- We know for sure that only the apartment units that are on fire have victims in them

Mission Plan (You may refer back to these instructions during your mission):

- Enter the building from the stairwell on the ground floor. You and your teammate will start searching the apartment units starting from floor 1, going up to the 2nd, and finally the 3rd floor. You must finish searching all the affected unit(s) on the lower floors before going to the upper floors.
- Search THOROUGHLY inside the apartment units (corners, around furniture, every nook and cranny possible)
- You and your teammate must always stay together at all times, but you are encouraged to split up inside the same apartment unit to expedite the search (i.e., BOTH OF YOU must be present in the same apartment unit, but may separate within that SAME apartment when searching)
- When you have found a fire, approach close enough without crossing or walking into it, jump twice (press spacebar 2X) then say, "Fire located" to report what you've found and where to your teammate. Resume your search IMMEDIATELY afterwards. If you do not jump TWICE and say "Fire located," it will be regarded as if you HAVE NOT FOUND the fire at all, even if you notice them.
- When you have found a victim, approach him/her, say "Victim located," jump twice (press spacebar 2X), report to your teammate where the person is, and resume your search IMMEDIATELY afterwards. If there is any furniture or if the victim is too close to the fire, stand & jump at the safest, closest distance possible. If you do not jump TWICE and say "Victim located," it will be regarded as if you HAVE NOT FOUND the victims at all, even if you notice them.
- If you think your teammate has found the same fire or victim that you have previously encountered, communicate this to him or her. If you have found the same fire or victim that you think your teammate has previously encountered, communicate this information to him or her
- You do not need to see your teammate's reported finding and vice versa
- You have 10 minutes from the moment you enter the premise to finish this mission
- Ignore flames licking the ceilings or the floors
- Your team will exit by climbing to the rooftop
- **Under no circumstances should your team deviate from this plan.**

- **Unless you feel any discomforts, you must NOT give up on the mission under ANY circumstances**
- Each of you will be inside of a car separate from your teammate at the beginning of the scenario. Please drive straight and park behind the large fire with the tall black smoke (this fire is just a landmark and **not** part of your mission)
- Before you enter the premise, please wear a safety breathing mask by pressing the button numbered "8" on the base of the joystick

Emergency Call 3

Information from Dispatch Center:
We have received a fire emergency call about a fire in seven-storey office building and the following information:

- Fire affects floors 4, 5, and 6. Your team will ONLY search these 3 floors.
- There are a total of 8 victims distributed across the three floors

Location	# of fire	# of victims
Floor 4	2	4
Floor 5	1	2
Floor 6	1	2

Mission Plan (You may refer back to these instructions during your mission):

- To get to the staircase to the target floors, go to the door straight ahead from the office's lobby main entrance and turn very sharp to the right
- Your team will start the search starting on floor 4 before going to floor 5 and 6. You must finish searching the lower floor(s) before ascending to the upper floor(s).
- Exit from the same stairwell you entered from and exit building through the lobby's main door
- As there are fire and victims on EVERY FLOOR, try not to move to the next floor unless you are sure you have found all victims and fire!
- Search THOROUGHLY (corners, around furniture, every nook and cranny possible)
- You and your teammate must stay together and must be on the same floor at all times, but you are encouraged to split up while on the same floor to expedite the search
- When you have found a fire, approach close enough without crossing or walking into it, jump twice (press spacebar 2X) then say, "Fire located" to report what you've found and where to your teammate. Resume your search IMMEDIATELY afterwards. If you do not jump TWICE and say "Fire located," it will be regarded as if you HAVE NOT FOUND the fire at all, even if you notice them.
- When you have found a victim, approach him/her, say "Victim located," jump twice (press spacebar 2X), report to your teammate where the person is, and resume your search IMMEDIATELY afterwards. If there are any furnitures or if the victim is too close to the fire, stand & jump at the safest, closest distance possible. If you do not jump TWICE and say "Victim located," it will be regarded as if you HAVE NOT FOUND the victims at all, even if you notice them.
- If you think your teammate has found the same fire or victim that you have previously encountered, communicate this to him or her. If you have found the same fire or victim that you think your teammate has previously encountered, communicate this information to him or her

- Exit from the same stairwell you entered from and exit building through the lobby's main door
- Ignore flames licking the ceilings or the floors
- You have <u>10 minutes</u> from the moment you enter the building from the lobby to finish this mission
- **<u>Under no circumstances should your team deviate from this plan.</u>**
- **<u>Unless you feel any discomforts, you must NOT give up on the mission under ANY circumstances</u>**
- Each of you will be inside of a car separate from your teammate at the beginning of the scenario. Please drive straight and park behind the large fire with the tall black smoke (this fire is just a landmark and **not** part of your mission)
- Before you enter the premise, please wear a safety breathing mask by pressing the button numbered "8" on the base of the joystick

Emergency Call 4

Information from Dispatch Center:

We have received a fire emergency call about a fire in a seven-storey office building and the following information:

- Fire affects floors 1, 2, and 3, but exact locations are unknown. Your team will ONLY search these 3 floors!
- Note: You need to take the stairs to go up to floor 1. To find the staircase, go to the door straight ahead from the office's lobby main entrance and turn very sharp to the right.
- Elevator is not working
- We know there are people to be located within those three floors, but we do not know how many victims are trapped or how the victims are distributed across all 3 floors

Mission Plan (You may refer back to these instructions during your mission) :

- Your team will enter from the lobby and go upstairs to floor 1 before going to floor 2 and 3. You must finish searching the lower floor(s) before going up to the upper floor(s).
- As there are fire and victims on EVERY FLOOR, try not to move to the next floor unless you are sure you have found all victims and fire!
- Search THOROUGHLY (corners, around furniture, every nook and cranny possible)
- You and your teammate must stay together and must be on the same floor at all times, but you are encouraged to split up while on the same floor to expedite the search
- When you have found a fire, approach close enough without crossing or walking into it, jump twice (press spacebar 2X) then say, "Fire located" to report what you've found and where to your teammate. Resume your search IMMEDIATELY afterwards. If you do not jump TWICE and say "Fire located," it will be regarded as if you HAVE NOT FOUND the fire at all, even if you notice them.
- When you have found a victim, approach him/her, say "Victim located," jump twice (press spacebar 2X), report to your teammate where the person is, and resume your search IMMEDIATELY afterwards. If there are any furnitures or if the victim is too close to the fire, stand & jump at the safest, closest distance possible. If you do not jump TWICE and say "Victim located," it will be regarded as if you HAVE NOT FOUND the victims at all, even if you notice them.
- If you think your teammate has found the same fire or victim that you have previously encountered, communicate this to him or her. If you have found the same fire or victim that you think your teammate has previously encountered, communicate this information to him or her
- Exit from the same stairwell you entered from and exit building through the lobby's main door

- Ignore flames licking the ceilings or the floors
- You have 10 minutes from the moment you enter the building from the lobby to finish this mission
- **Under no circumstances should your team deviate from this plan.**
- **Unless you feel any discomforts, you must NOT give up on the mission under ANY circumstances**
- Each of you will be inside of a car separate from your teammate at the beginning of the scenario. Please drive straight and park behind the large fire with the tall black smoke (this fire is just a landmark and **not** part of your mission)
- Before you enter the premise, please wear a safety breathing mask by pressing the button numbered "8" on the base of the joystick

Appendix L – Participant Feedback

Participant Feedback (after all sessions completed)

From a scale of 1 to 5, how hard was the overall task (through all 4 scenarios)?

1	2	3	4	5
Very difficult	Somewhat difficult	Not too easy, not too difficult	Somewhat easy	Very easy

From a scale of 1 to 5, how hard were the overall missions in the office building?

1	2	3	4	5
Very difficult	Somewhat difficult	Not too easy, not too difficult	Somewhat easy	Very easy

From a scale of 1 to 5, how hard were the overall missions in the apt building?

1	2	3	4	5
Very difficult	Somewhat difficult	Not too easy, not too difficult	Somewhat easy	Very easy

From a scale of 1 to 5, how complex (confusing to navigate) is an office floor? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how complex (confusing to navigate) is a typical apartment? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how complex (confusing to navigate) is an apartment's floor (the apartments in one floor combined with the corridor)? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how difficult was it for you to orient yourself (knowing where you are) inside a floor in the office building? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how difficult was it for you to orient yourself (knowing where you are) inside an apartment? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how difficult was it for you to orient yourself (knowing where you are) inside a floor in the apartment building? Please circle the appropriate number

1	2	3	4	5
Very complex	Somewhat complex	Not too simple, not too complex	Somewhat simple	Very simple

From a scale of 1 to 5, how would you rate the overall training instruction?

1	2	3	4	5
Very vague	Somewhat vague	Neither vague nor clear	Somewhat clear	Very clear

From a scale of 1 to 5, how easy was it for you to use the joystick?

1	2	3	4	5
Very easy	Easy	Not too easy/not too hard	Hard	Very hard

Did you feel that you got use to the joystick as the experiment progressed?

1	2	3
Yes	Somewhat	No

Please indicate any of the following symptoms should you experience them at any moment during the experiment:

Eyestrain: Yes/No. If yes, please indicate the intensity level by circling the appropriate number below

1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

Headache: Yes/No. If yes, please indicate the intensity level by circling the appropriate number below

1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

Blurred vision: Yes/No. If yes, please indicate the intensity level by circling the appropriate number below

1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

Vertigo: Yes/No. If yes, please indicate the intensity level by circling the appropriate number below

1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

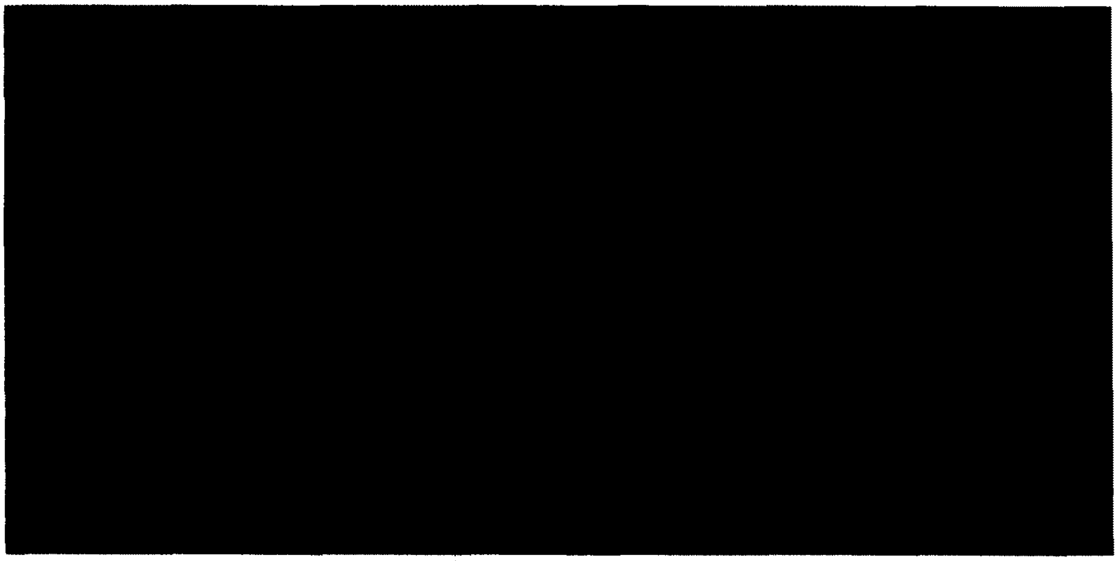
Imbalance: Yes/No. If yes, please indicate the intensity level by circling the appropriate number below

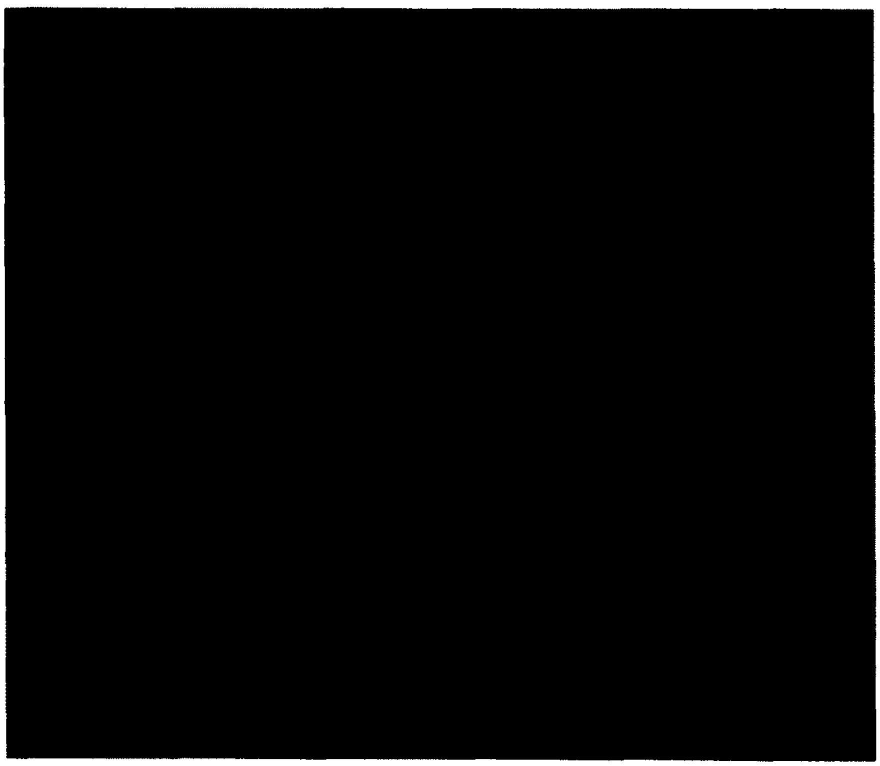
1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

Nausea: Yes/No. if yes, please indicate the intensity level by circling the appropriate number below

1	2	3	4	5
Very high	High	Moderate	Mild	Very mild

Appendix M - Office and Apartment Buildings





Appendix N - Participant's View of Virtual Environment

Appendix O - Joystick Photo

Joystick

Appendix P - Floor Layouts of the Apartment and Office Buildings