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Virtual Reality Based Spacecraft Emergency Egress 3D Navigation Training

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ABSTRACT

BACKGROUND: Astronauts have reported spatial disorientation and navigation problems inside spacecraft whose interior visual vertical direction varies from module to module. If they had relevant preflight practice they might orient better. This experiment examined the influence of relative body orientation and individual spatial skills during VR training on a simulated emergency egress task. **METHOD:** During training, 36 subjects were each led on 12 tours through a space station by a virtual tour guide. Subjects wore a head-mounted display and controlled their motion with a game-pad. Each tour traversed multiple modules and involved up to 3 changes in visual vertical direction. Each subject was assigned to one of three groups that maintained different postures: Visually upright relative to the "Local" module; Constant orientation relative to the "Station" irrespective of local visual vertical; and "Mixed" (Local, followed by Station orientation). Groups were balanced on the basis of mental rotation and perspective-taking test scores. Subjects then performed 24 emergency egress testing trials without the tour guide. Smoke reduced visibility during the last 12 trials. Egress time, sense of direction (by pointing to origin and destination) and configuration knowledge were measured. **RESULTS:** Both individual 3D spatial abilities and orientation during training influence emergency egress performance, pointing, and configuration knowledge. Local training facilitates landmark and route learning, but station training enhances sense of direction relative to station, and therefore performance in low visibility. **CONCLUSIONS:** We recommend a sequence of local-, followed by station- and then randomized-orientation training, preferably customized to trainee's 3D spatial ability.

Introduction

Astronauts and cosmonauts have often reported spatial disorientation and spatial memory difficulties, even in the relatively small Vostok and Apollo spacecraft [15, 20]. In larger vehicles with complex 3-dimensional (3D) architectures - such as Mir and the International Space Station (ISS) - navigation[1] problems have been described as well. Shuttle visitors became lost, and even long-duration crews had difficulty visualizing spatial relationships among the interiors of certain modules [15]. Astronauts rely principally on visual cues because the usual terrestrial gravitational cues to the vestibular organs are absent. They orient by recognizing objects and surfaces familiar from preflight training in mockups. Crews generally train in 1-G in an upright body orientation relative to gravity, and therefore remember a specific surface as a "floor" or a "wall" or a "ceiling." Their "cognitive map" [13] of a module's interior arrangement is defined and remembered relative to this reference frame, often referred to as the local "visual vertical" [15, 16, 19]. Once in orbit, astronauts face two problems: First, they can float into any body-orientation relative to the environment. Therefore, recognizing their orientation relative to their cognitive map of the local environment inherently requires a complex 3D mental rotation. If crewmembers do not pay careful attention to their orientation, they tend to perceive whichever surface happens to lie beneath their feet as a "floor" and, correspondingly, any surface parallel to their body-axis as a "wall." Such changes in perceived surface identity are referred to as "Visual Reorientation Illusions" (VRIs) [14, 15, 17], and are a form of intra-module spatial disorientation.

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[1] In this paper "navigation" refers to coordinated and goal-directed movement through the larger environment [11] - in this case inter-module movement - and knowledge of spatial relationships beyond direct view, whereas "spatial orientation" refers to knowledge of intra-module angular orientation and location, based primarily on local visual cues.

Second, adjacent modules in a spacecraft may be connected so that the local visual vertical (floor-to-ceiling) axes are not coaligned. Hence the crew, which learned the modules separately and unconnected, cannot easily determine or remember these inter-module spatial relationships. When transiting such modules, each change in the direction of the local visual vertical is potentially disorienting and makes it difficult to keep track of the direction towards an unseen destination, in a module beyond the one being entered, in three dimensions. As a result, crews typically remember routes as a sequence of memorized landmarks and turns, a strategy many people use on Earth when they lack an integrated "cognitive map" (also sometimes called "survey knowledge" [22]) of the entire environment. However if visibility is reduced, e.g. due to fire or water fog due to rapid decompression, landmarks may not be as easily seen, so it becomes more important to maintain an overall sense of direction relative to the entire station and to instinctively know which way to turn in order to reach a destination. Because astronauts are trained in a single body orientation on the ground, and in modules that are not connected in their physical flight configuration, we fully expect to see negative transfer of training to performance on procedures (e.g., depressurization, firefighting, or egress) that generically require rapid transit and/or spatial judgments within and between spacecraft modules.

To keep track of their orientation and location relative to the spacecraft as a whole, the crew must consider one module or group of similarly aligned modules as the overall spacecraft ("station") reference frame. To interrelate the modules with incongruently aligned visual verticals to the station frame, they can then presumably learn to perform the mental rotations needed to navigate, or attempt to re-establish their cognitive maps of the incongruent modules [16]. However experiential relearning is difficult because intervening walls prevent the astronauts from directly viewing the spatial relationships of landmarks in different modules. Also, local visual vertical cues provide a powerful reorienting reference that can keep them from recollecting the orientation of the larger “station” reference frame. Maintaining a “station” body orientation in an incongruently aligned module may trigger a VRI, and cause momentary disorientation in the local frame. Thus, the absence of gravity, the variability of body orientation, the inconsistency of the modules’ visual verticals, and the difficulty of acquiring and maintaining an integrated cognitive map of the entire spacecraft are thought to be major causes of astronauts’ difficulty with orientation and navigation [1, 2, 15, 16, 19].

It has been suggested that virtual reality (VR) techniques could be used in the early portions of training to provide astronauts with orientation and navigation practice for Intra Vehicular Activities (IVA), and allow them to develop an integrated cognitive mental map of the spacecraft in the actual flight configuration [18, 19]. VR simulation is now widely used for orientation and navigation studies in terrestrial 1-G environments, and it has been shown that spatial knowledge acquired in a virtual environment can be transferred to real situations [4]. VR simulation has been used for emergency evacuation research and firefighter training on the ground [3]. For the past decade, VR-based Extra Vehicular Activity (EVA) training [9, 26] has routinely been used by Shuttle astronauts as an adjunct to neutral-buoyancy training to allow crews to become visually familiar with the exterior of Shuttle and ISS, and to preplan EVA routes. Although there have been no formal verifications of transfer-of-training, astronauts clearly find the VR EVA training helpful.

For IVA training, Harm and colleagues [6, 24] pioneered the use of VR as a prototype disorientation training countermeasure using a domed-, projection-style preflight adaptation training (PAT) simulator, and a relatively simple two-module spacecraft with congruent visual verticals. Harm and Parker [6] reported that astronauts who had PAT training in IVA orientation and navigation tasks had less severe symptoms of space-motion-sickness in-flight. Stroud et al. [24] later showed that PAT training in a variety of different initial body orientations improved navigation performance.

Aoki et al. [1, 2], Lathrop and Kaiser [8] and Vidal et al. [25] studied navigation performance in more architecturally complex virtual 3D mazes. As path complexity increased, navigation performance degraded significantly. Oman and colleagues [18, 19, 21] investigated 3D orientation skills in a virtual cubic room representing a space station node module and found significant correlation between performance and scores on conventional 2D and 3D object mental rotation tests such as the Card Rotation test, the 3D Cube Comparisons test ("Cube") [5], and also the Group Embedded Figures Test [27]. Oman et al. [16] also showed that in addition to the ability to rotate objects mentally, skill in visualizing an environment from a novel perspective may be important, as measured by a computerized Perspective Taking Ability Test (PTA) [7]. We therefore hypothesized that individual differences in both mental rotation and perspective-taking abilities could also be an important determinant of 0-G spatial orientation and navigation strategies and performance.

Due to constraints on crew time, it has not been possible to do controlled experiments on astronaut orientation and navigation skills while in orbit. However, to better understand the scientific problem, and to investigate possible VR based preflight training strategies, we studied 3D spatial learning in a group of normal subjects while they learned to perform an emergency egress navigation task in an architecturally complex virtual space station. The principal manipulation was body orientation of the subject relative to the spacecraft. Is it better for naïve subjects to be trained in a constant body orientation relative to the overall station reference frame, accepting that they would not be visually upright in some modules? Alternatively, is it better for subject to maintain a visually upright body orientation in each module, accepting that their body orientation relative to the station reference frame will not be constant? Our hypothesis was that most subjects would find it easiest to learn landmarks within a given module while remaining locally visually upright. Based on how humans normally learn to navigate incongruous spaces on Earth [22] we expected they would initially navigate using a simple landmark and route strategy: memorizing which module was connected to which. When in the nodes that interconnect multiple modules, we expected they would choose the correct path by simply looking through all the hatches, rather than trying to keep an overall sense of direction. We expected that if we asked them about the sequence of modules to be traversed on a particular path, they would do well. However, if at the start of each emergency egress we asked them to point in the direction of the destination, we expected that they might have difficulty. Similarly when they arrived at the destination they would also have trouble pointing back to the starting point. We also expected that the performance of those who used only landmark and route strategies would suffer disproportionately under conditions of reduced visibility. In that case, if subjects could not see their landmarks and recognize which module was which, they would not know which way to turn. They might enter the wrong module, recognize they had made a turning error, return to the node, and try another direction. This suggested a second experimental manipulation: vary visibility inside the modules (normal or obscured by smoke).

An alternative strategy, of course, is to train subjects with their bodies consistently oriented upright relative to the overall station frame, accepting the fact that it would be initially harder for them to learn the spatial layouts of the incongruently aligned modules, and that they might occasionally experience VRI disorientation in them because their feet were pointed towards a wall, rather than a floor. In early stages of training they might take longer to find their way than those trained locally upright. Because they were not relying so much on landmark and route strategies, their knowledge of module sequence along various egress paths might not be as good as that of the locally upright trained group. However we expected that eventually they would do better than the locally trained group in maintaining their overall sense of direction, and consequently be able to point more accurately to the start or the end of the egress paths, and make fewer turning errors.

A third potential VR training strategy - which we refer to as “mixed” - could blend the advantages of the two previous techniques: Subjects would initially be trained locally upright in all modules. This should facilitate learning local cognitive maps and development of landmark and route knowledge. Subsequently, they could be trained in a “station” orientation, in order to improve sense of direction (e.g., forward and backward pointing) and performance in smoky conditions. We hypothesized that for most subjects, mixed training would be best.

Finally, we hypothesized that those subjects with strong mental rotation and perspective taking skills (as measured on the Cube and PTA tests described earlier) would do best regardless of training manipulation. However we expected that those trained only locally upright would more likely have become reliant on landmark and route strategies, and would have trouble if tested under conditions of reduced visibility.

Our experiment was designed to test all these hypotheses.

Methods

The experimental protocol was approved in advance by MIT's Committee On the Use of Humans as Experimental Subjects (COUHES). Subjects gave written informed consent before beginning the experiment, and were paid $10 per hour.

Subjects

Forty-seven subjects were originally recruited, all students and staff from the Massachusetts Institute of Technology. All subjects were administered the Cube Comparisons and Perspective Taking Ability tests. All denied history of visual or vestibular disorders. Nine failed to complete the experiment (seven because of nausea, one because he was unable to learn the testing task, and one for personal reasons). Two others who had low outlier Cube and PTA scores were treated separately. Therefore, the analysis was based on data from 36 subjects (18 females and 18 males, aged 19-39 with a mean age of 25.6 yr). The (median, range) of the spatial ability predictor test scores were, respectively, Cube (27.0, 29.0) and PTA (21.6, 13.8), within normal limits.

Experiment Design

The subjects were divided into three treatment groups (Training Orientation) that were balanced on the basis of gender (6 men and 6 women in each of the 3 groups), and by Cube and PTA test scores[2]. The experiment was conducted in two phases, training followed by testing. The procedures within each phase were different, as will be detailed later. Subject orientation manipulation (Local, Station, or Mixed orientation training) was the between-subject blocking factor. Gender was a between-subject factor for analysis. Standardized (z-) Cube test score was used as a covariate in some analyses to account for differences of natural aptitude of the subjects. During both training and subsequent testing trials, subjects traveled along a series of paths. A total of 24 trials (paths) were used during the testing phase. Path order was randomized, and path direction was balanced. Data was analyzed over four successive groups of six trials, each which we refer to as a "quarter." Visibility was a within-subjects manipulation: the first two quarters of testing were conducted without smoke, followed by two quarters with smoke. Testing in the reverse order with smoke first was impractical, since subjects could not see well enough and yet know enough to complete the egress task.

The seven dependent variables in the testing phase were: egress task completion time, the number of turns made per trial, absolute pointing angular error and response time for both pointing forward (to destination) and backward (to origin), and the number of errors made in describing the configuration after the tests were complete. Analysis was performed using Systat V11 (Systat Software, Inc., San Jose, CA).

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[2] Gender effects are often reported in spatial ability testing. A two-way (3 (Orientation) × 2 (Gender)) between-subject Analysis of Variance (ANOVA) of the Cube and PTA scores showed a significant effect of Gender on PTA score ($F(1, 30) = 6.065$, $p = .020$), but no significant between group effect of Orientation or Orientation × Gender effects, and no significant effects on Cube score.

Equipment

During both training and testing, subjects sat erect in a fixed chair, and viewed the interior of a virtual space station (Fig. 1) through a high-resolution (640 × 480 pixels per eye) color stereo head-mounted display (HMD, Model V-8, Virtual Research Systems, Inc., Aptos, CA) that had a 60 degrees diagonal field of view and 100% stereo overlap. Subjects were free to look around the virtual environment. Rotational head movement was detected by inertial/acoustic hybrid head-tracking system (IS-600 MkII Plus, InterSense, Inc., Bedford, MA). The virtual space station was created with 3D Studio Max (Autodesk, Inc., San Rafael, CA) and the scene rendered by Python/OpenGL-based virtual-reality software (Vizard, WorldViz, Inc., Santa Barbara, CA) running on a Windows personal computer. Scene update rate was 27-30 Hz. The subjects used a hand controller (Thrustmaster FireStorm Dual Analog 3, Guillemot Corp., France) with 12 buttons to move virtually through the environment. Subjects controlled their angular orientations in 90-degree increments, and translations in one-meter increments so that their body axis always remained aligned with one of the three major axes of the station. The software smoothed their movements.

[**Figure 1** here]

Virtual Space Station

The interior architecture of the virtual space station (VSS) (Fig. 1) generally resembled that of the ISS in its originally planned final configuration, and consisted of seven rectangular ($2 \times 2 \times 6$ m^3) modules, three cubic ($2 \times 2 \times 2$ m^3) nodes, and a tunnel-like Pressurized Mating Adapter (PMA). One of the rectangular modules represented the interior of a docked Soyuz-like spacecraft. Each module had a hatch at one end, while each node had up to four open hatches interconnecting to adjacent modules or the PMA. Subjects inside a node could see landmarks in the adjacent modules only in the no-smoke condition. Subjects could pass through module hatches without changing their orientation, except they had to pitch forward when transiting the narrow circular hatches of the PMA. The latter maneuver made it somewhat more likely that they would lose their sense of direction when transiting the PMA.

Most of the module and node interior surfaces were textured using photographs of actual ISS interior surfaces or their ground mockups. The rectangular modules were assigned names based on visually obvious internal landmarks (e.g., “US-Lab”, “Soyuz vehicle”, “Airlock”, etc.). Each module had a primary local visual vertical, defined by the location of equipment, rack labeling, lights, and the shape of hatch frames, etc. Five of the modules had congruently aligned visual verticals, which defined the overall VSS “station” reference frame. However, the visual verticals of two others (the Soyuz and Centrifuge modules) were oriented at 90 degrees to the station reference frame.

Procedure

The subjects were given written instructions. Next, they familiarized themselves with the hand controller button functions for 5 - 10 minutes by rotating and translating their body inside a practice spacecraft-like virtual environment different from the VSS.

During the training phase, which required about 45 minutes, subjects were led through a series of 12 tours. All subjects performed the same tours in the same order. If fatigued or uncomfortable, they could take a break between tours. At the beginning of each tour, subjects were placed in one of seven modules. Each tour’s path started from the mid-point of one of the six modules on opposite sides of the VSS, passed through the three nodes, the PMA and the US-Lab located in the middle of the VSS, and terminated at the mid-point of one of the modules on the opposite side of the VSS.

During training the subjects followed a virtual astronaut tour-guide, and were instructed to maintain the body-orientation of that virtual guide at every stage. The orientation of the tour guide (and thus, that of the subjects) during training was the same for all subjects within an experimental group. Each group maintained one of three orientations: 1) Local orientation: Subjects faced along the tour path always upright with respect to the visual vertical in the module they were in at the time. 2) Station orientation: Subjects maintained constant orientation, always aligned with the visual upright direction of the five modules that defined the "station" reference frame. 3) Mixed orientation: Local orientation during tours 1-6 followed by Station orientation during tours 7-12.

There was no time pressure during the training tours and visibility was always good. Subjects were encouraged to look around and move about in each module and visually examine local landmarks. Each module had at least one prominent visual interior landmark associated with its name, e.g., a NASA logo on the wall of the US-Lab, that made it easy for subjects to recognize and remember which module was which. To learn the name of each module, subjects were shown a menu of module-names and were asked to select an appropriate one. After making their selection, the correct name of the module was displayed.

Next, a virtual astronaut tour guide appeared in the module and the subjects were instructed to assume the same body orientation as the tour guide, and to follow the guide to the next module. The tour guide paused after passing each node, so subjects could catch up. After subjects arrived at the end of each tour, they were asked to point back to the initial starting point of the tour path by calling up a virtual HMD crosshair and turning their head so it pointed in the correction direction (“pointing backward task”). During training they were not told if they had pointed correctly. Subjects then proceeded to the next training tour. Over the 12 training tours, subjects visited every module twice (except the US-Lab, which appeared in all 12 tours). Subjects then took a short break.

Next, subjects’ ability to use their environmental knowledge to perform a simulated emergency egress task was tested in 24 testing phase trials, in four quarters of six egress trials each. Testing required about 45 minutes. The first quarter required the subjects to transit six different egress routes. Two of the egress routes were identical to two used in training. In the second quarter, the subjects transited the same routes, but in the opposite direction. The third and fourth quarters used the same routes as the first two, but visibility was reduced to about 1-2 meters using simulated smoke. This meant that subjects in a node could not recognize which module was which simply by looking through the hatch, and had to rely on their sense of direction.

In each egress testing trial, subjects were inserted at the midpoint of one of the six modules on opposite sides of the station, facing its open hatch, and were told their egress destination - one of the modules on the other side of the station. Subjects were instructed to recognize the module they were in, to determine their orientation relative to the overall spacecraft and to point the HMD virtual crosshair (forward) toward their destination as quickly as possible. We called this the “pointing forward task”. Absolute pointing forward angular error and the response time when pointing forward were measured. No feedback on pointing error was provided during testing. Subjects were then asked to move virtually to the mid-point of the destination module as quickly as possible, as they would in an emergency situation. Upon reaching the destination, the egress time and the number of turns made by the subject while en route were measured. The subjects were then instructed to turn around and point back to the start of their egress path (pointing backward task) as quickly and accurately as possible. Pointing backward angular error and response time were measured.

Finally, after the testing phase trials, subjects were asked to verbally describe to the experimenter the configuration of the VSS. This had to be done from memory - subjects were not allowed to draw pictures. Based on the verbal description, the experimenter sketched a drawing of the VSS configuration, and then showed it to each subject who corrected the figure if necessary and confirmed that the diagrammed sequence of modules and their orientation were as they remembered. The number of errors in module placement and orientation were subsequently tabulated. If subjects described a module in the correct sequence but the orientation incorrect, it was scored as half an error. One local orientation trained subject was completely unable to describe the VSS configuration.

Results

Effect of training body orientation on emergency egress task performance and configuration knowledge.

Data for forward and backward pointing error and egress time and configuration knowledge are summarized in Figures 2-3 and Table I, respectively. Results generally supported our expectations: Station-trained subjects would consistently have a better sense of direction (as indicated by consistently lower pointing errors, Fig. 2), and could correctly describe the actual configuration of the station (Table I), but the locally trained group would acquire landmark and route knowledge more rapidly, and egress faster--at least under good visibility conditions, when they could see their landmarks. As expected, the mixed training group egressed as quickly as the locally trained group did, and pointed as accurately as the station trained group did. However, their retrospective descriptions of the VSS configurations were less accurate than those of the station trained group. As detailed later, it was the individual subject's 3D spatial skills (as measured by Cube and PTA tests) that more accurately predicted performance at the testing phase tasks.

[**Figure 2** here]

[**Figure 3** here]

[**Table I** here]

As expected, the Station orientation made many fewer VSS configuration description errors than the other two groups (Table I). The difference between orientation groups was significant ($\chi^2 = 6.9$, df = 2, $p < .05$). The poorer performance of the mixed group at least suggests that more trials of station training might have improved their station configuration knowledge.

[**Table II** here]

Table II shows the Pearson correlation coefficients for the seven dependent variables and two performance predictor tests (Cube and PTA). As expected, many of the dependent variables were significantly correlated with one another. Presumably subjects who became disoriented made extra, unnecessary turns. Pointing response times correlated significantly only with each other, but not with other measures. The individual subject's Cube-scores correlated with forward and backward pointing errors, egress time, and the number of turns made. PTA scores correlated with Cube-scores, egress time and the number of turns made, but only with forward pointing. Of our two predictor tests, Cube scores were thus slightly more predictive than PTA.

To assess effect magnitudes quantitatively, repeated measures General Linear Model (GLM) ANOVAs were conducted on the egress time, forward and backward pointing angular error and pointing response time data. Orientation and Gender were between-subject factors; Visibility and Quarter were within-subject factors, and Cube-score (rather than PTA) was chosen as the covariate.

Analysis of pointing error data (Fig. 2) showed that an individual subject's Cube Score was statistically the dominant predictor (Cube-score ($F(1, 31) = 10.1$, $p < .005$). The effect of Quarter on pointing error was not significant. This was expected since no feedback was provided. Main effects of Orientation, Gender and Visibility were not significant. However a sub-analysis that factored in the specific egress spatial path showed that training groups responded differently. The locally upright trained group showed larger angular error on specific egress paths[3].

Analysis of egress time data (Figure 3) also showed a significant effect of Cube-score ($F(2, 27) = 4.1$, $p < .05$) on egress time, but no main effect of Orientation, Gender, or Visibility, or their interaction effects. This is probably due to the different

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[3] Orientation × Path effect ($F(10, 155) = 2.1$, $p < .05$). We performed detailed analyses of this data set by specific spatial path configuration, seeking to understand how egress path spatial geometry influenced performance. Such data is useful to spacecraft architects, and those who design emergency egress paths. Because the focus of the present paper is on training and spatial abilities, these detailed results will be reported in another paper.

learning trend with and without smoke among the training groups. There was evidence of improvement through the four quarters only for the Station orientation (F(3, 27) = 7.4, p < .0001). Some improvement in egress time was anticipated, particularly during the first several testing trials, as subjects became more familiar with the emergency egress task. Unlike the training task, the egress testing task required speed, and the tour guide was absent. As we anticipated, introduction of smoke (Quarters 3 &4) had a major effect on egress time performance of the different groups. The locally-trained orientation group - the fastest without smoke, became the slowest when there was smoke. A contrast based on the repeated measures GLM ANOVA egress time model showed significant effect of Orientation × Quarter between Quarters 2 and 3 (before and after visibility was obstructed by smoke, F(2, 31) = 3.4, p < .05). One explanation may be that the station trained group had a better sense of direction relative to the station coordinate frame, and was more likely to turn the correct way in the nodes, even though they could no longer see landmarks in the adjacent modules.

Relationship between individual 3D spatial abilities and egress task performance

Since the ANOVA analysis highlighted the effect of individual 3D spatial abilities on performance, we ranked each of the subjects within each in each orientation training group by Cube score, forming three equally sized (n=4) 3D ability subgroups with high, middle, and low Cube scores within each orientation group. The divisions were consistent across orientation groups because the orientation groups had already been balanced using Cube-score. Egress-time results for these subgroups are shown in Figure 4. Among the lowest ability subjects (Figure 4, left), the Station orientation trained group egressed much more slowly than the average, whereas those trained in the Local orientation consistently performed best. We suspected that even though they had poor pointing ability and configuration knowledge, the low score, Locally trained group learned to perform the task using a landmark and route strategy, memorizing sequences of visual landmarks and modules, but not paying much attention to how the modules were oriented with respect to each other or maintaining a sense of direction relative to the station frame. However, the low Cube score subjects who were trained in the station orientation probably found the tilted visual scenes they occasionally encountered initially confusing. They did not achieve egress times comparable to those achieved by other subgroups until the final quarter of testing.

On the other hand, the high-ability subjects (Figure 4, right) performed well regardless of training orientation. They had superior pointing scores and configuration knowledge, and performed best of all the subgroups under reduced visibility conditions. However among them, those who trained only in the Local orientation had the most difficulty when visibility was reduced by smoke. One could speculate that this was because they had come to rely more on landmark and route strategies, and less on their sense of direction than subjects in the other subgroups.

Mixed regression analyses were performed on the effects of Orientation on egress time, separately by ability subgroup and visibility condition (Table III). Among the low-scoring subjects under no smoke conditions, the Local orientation trained group (73.5s) egressed an average of 44.4 seconds faster than the Station orientation group (117.9s). Among the high scoring subjects, the Local orientation trained group (81.3s) took more than twenty seconds longer to egress than the Station (58.9s) or Mixed (61.2s) orientation trained group in the smoke condition. These spatial ability and visibility dependent differences in egress performance were statistically significant (Table III) and are certainly large enough to suggest the effects could be operationally important.

[**Figure 4** here]

[**Table III** here]

Discussion

Due to the experiment's design, a decrement of performance due to smoke could be confounded by an improvement in performance due to practice. There is also some suggestion of this in the egress time data of the high spatial ability group, where the Station and Mixed orientation subjects achieved their best egress times despite the smoke, whereas the Local orientation subjects egressed more slowly. Nonetheless, we believe interpretation of the data is relatively straightforward.

As mentioned in the Methods section, two of the subjects originally recruited had low Cube and PTA scores, well below the 5th percentile. Their data was excluded from the final analysis because their extremely low Cube and PTA scores are not typical of the anticipated astronaut-trainee population. The performance of these two subjects was also in the outlier range: egress time was 45% longer and pointing errors 22% larger than other subjects. Outlier performances are also seen in other studies of human navigation performance (e.g., [1]).

Simulator sickness has been reported in many immersive VR training applications such as flight simulation, soldier training, and astronaut EVA training [9, 12], but can be mitigated by allowing frequent breaks, and optimizing visual and vestibular cue fidelity. In the present experiment, it is not entirely clear how sickness and performance are interrelated. Do those who are sick limit their head movements, and therefore perform worse? Or do those with poor spatial abilities need to look around more, and experience more sensory cue conflict and symptoms as a result? Of our 36 subjects, 29 mentioned in the post experiment interview that they occasionally had mild symptoms (e.g., dizziness, slight nausea). Seven (14.9%) of the 47 subjects originally recruited could not complete the experiment due to simulator sickness, a dropout rate comparable to that (12.9 %) reported by Stanney et al. [23] for subjects performing a simulated terrestrial virtual navigation task.

Several limitations of the present study should be acknowledged. First, although learning effects were most evident during Trials 7-12, had the subjects been able to tolerate much longer training and testing it is possible that higher levels of performance might have been achieved by some subjects. We focused on what could be achieved in one session lasting several hours. Second, also because of time constraints, we did not attempt to continue training by including an additional phase in which each subject's relative orientation was randomly varied within each module. Doing this would have broadened the trainee's visual experience in the local environment from visually tilted and inverted viewpoints, and would have been even more challenging. The advantages of random orientation training have already been demonstrated in several previous experiments [19, 21, 24], and were not the focus of this experiment. Third, had we employed a VSS configured like the Mir station with its architecturally inverted Core (Base Block) Module, subjects might have found it even more difficult to orient. Although the ISS-like VSS configuration we studied was NASA relevant, it may not represent the most architecturally challenging case. Fourth, our subjects were students and staff, and were naïve about the architecture of the VSS at the start of the experiment. They were not allowed to study any pictures or maps of the VSS layout at any point during testing or training. Real astronauts are already familiar with the flight configuration of ISS, and may have prior experience in mockups of individual modules, albeit probably only in the visually upright condition. Finally, it should be emphasized that our subjects navigated using gamepad buttons in an immersive virtual environment, not by physically translating in an actual space station. They sat erect, and the presence of gravity may have made them more susceptible to disorientation after a virtual pitch or roll of the environment. Although - as noted earlier - VR simulations have been found to predict real-world navigation performance, we cannot be certain 3D configuration knowledge and navigation skills acquired through this type of VR training will transfer to orbital flight unless a comparable validation experiment is eventually done using astronauts in orbit. Our goal in these experiments was to understand better how humans acquire the 3D orientation and navigation skills generically required for response to emergencies, and how best and most efficiently to supplement astronauts' current training regimen so they have 3D configuration knowledge and maintain sense of direction in reduced visibility conditions.

Conclusions

Considering the results, what sequence of relative orientations should be used while training astronauts for emergency egress? If training cannot be customized to the individual astronaut's spatial ability (e.g., using Cube and/or PTA score), it may be argued that a Mixed orientation sequence is best. Such training would begin with locally (visually) upright training so subjects easily learn individual modules and gain landmark and route knowledge, proceed through station-orientation training, which enhances sense of direction, and - for reasons described in the previous section - conclude with additional random orientation practice. Low visibility conditions are easily simulated using VR, and should be introduced early enough so that astronaut trainees realize the vulnerability of landmark and route strategies, and importance of learning to maintain their sense of direction relative to the station coordinate frame.

Certainly the <u>least</u> advantageous prescription is pure locally-upright training, which, among the alternatives tested, most closely corresponds to what astronauts and cosmonauts do now. The present experiment demonstrates that locally upright training results in weak configuration knowledge. Locally-upright trained subjects may be able to perform emergency egress, but they may take longer than normal and make more wrong turns in low visibility condition, show poorer pointing performance in many cases.

Our results do suggest potential advantages if training can be customized to each astronaut's spatial abilities, as assessed for example by the relatively brief 3D Cube mental rotation or Perspective-Taking tests. Trainees with lower spatial abilities should begin with the Local orientation training, but should then receive an extended period of the Station-oriented training until their pointing ability and configuration knowledge reach performance criteria. The Local training of those with high spatial abilities can be correspondingly accelerated.

When, relative to flight, should the orientation and navigation aspects of egress training be undertaken? Studies of spatial knowledge retention in multiple module spacecraft are needed, but Richards et al. [19] did show that detailed 3D configuration knowledge of individual modules acquired from VR training is retained for at least a month. Other more procedural (as opposed to spatial) aspects of emergency egress response may require more frequent practice.

Other VR techniques could also be exploited to enhance training of the 3D configuration of the spacecraft. For example, trainees could be allowed to momentarily “see through” the walls of the local module. Alternatively, a virtual “doll-house-like” model of the entire station interior could be provided. The latter has been shown to improve the wayfinding of normal subjects in a simulated space station [10].

Steps could also be taken to help crews quickly visually identify the local and station coordinate frames. Russian space station modules use consistent floor, wall, and ceiling colors to make it simpler to identify the local frame. For example, colored tapes between equipment racks could designate Station coordinates (e.g., red tape for “port” side, green for “starboard”, brown for “deck”, and gray for “aft”) while the Local module frame can be indicated by the wall-surface color (dark floor, bright ceiling). Such schemes have been shown to be useful in VR training simulations [2].

Finally, we think it is important to interview previously flown crews to determine what visual landmarks and navigation strategies they currently use. One should teach trainees a spatial framework of operationally useful local and global orientation and navigation landmarks, and then test their ability to visualize spatial relationships between them.

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Table I. Configuration description.

Configuration description	Number of modules placed in wrong position	Local	Station	Mixed
Correct	0	2	8	3
Incorrect	0.5	3	1	4
	1	3	2	2
	2	3	1	2
	3	0	0	1
	Incorrect total	9	4	9

Table II. Pearson correlation coefficient matrix for the mean of Cube/PTA test scores and VR task performance.

	CUBE	PTA	P_FW	RT-P_FW	P_BW	RT-P_BW	Turns	Egress_T	Config Error
CUBE	--	.002	.006	.443	.005	.655	.001	.003	.061
PTA	.508***	--	.037	.919	.163	.231	.004	.008	.402
P_FW	-.458**	-.355*	--	.767	<.0005	.537	<.0005	.001	<.0005
RT-P_FW	-.134	-.018	.052	--	.879	.002	.257	.127	.618
P_BW	-.465***	-.241	.880***	-.027	--	.080	<.0005	<.0005	<.0005
RT-P_BW	-.078	-.208	-.108	.503***	-.300	--	.104	.171	.512
Turns	-.537***	-.473***	.628***	.197	.571***	.280	--	<.0005	.026
Egress_T	-.495***	-.443**	.541***	.263	.561***	.237	.746***	--	.067
Config Error	-.320	-.146	.595***	-.087	.589***	-.115	.377*	.313	--

The lower diagonal shows the Pearson correlation coefficients and the upper diagonal shows their p-levels of significance. Abbreviations: P_FW/P_BW = Absolute angular errors for Pointing Forward/Backward; RT-P_FW/RT-P_BW = Response time for Pointing Forward/Backward; Turns = Number of turns a subject made per trial; Egress_T = Egress time; Config Error = Number of modules placed in wrong position in the post-test. * $p < .05$, ** $p < .01$, *** $p < .005$

Table III. Estimated egress time of the Low scoring subjects without smoke and that of the High scoring with smoke based on mixed regression.

Variable	Estimated time in seconds	Standardized error	Z	*p*-value
Low scoring, no smoke				
Intercept	94.35	6.67	14.15	<.0005
Local	-20.90	9.43	-2.22	.027
Station	23.55	9.43	2.50	.013
(Mixed)	(-2.65)	(--)	(--)	(--)
High scoring, in smoke				
Intercept	67.15	3.95	17.01	<.0005
Local	14.23	5.58	2.55	.01
Station	-8.24	5.58	-1.48	.14
(Mixed)	(-5.99)	(--)	(--)	(--)

Figure Caption

Figure 1. Virtual Space Station (VSS) and the module names used in the experiment. Arrows show direction local visual "up" in each module.

Figure 2. Angular pointing error, forward and backward, by orientation training group. Error bars represent +/- 1 SEM.

Figure 3. Egress time by the orientation training group. Error bars represent +/- 1 SEM.

Figure 4. Egress time by orientation training group and Cube-score level. Error bars represent +/- 1 SEM.

Figure 1

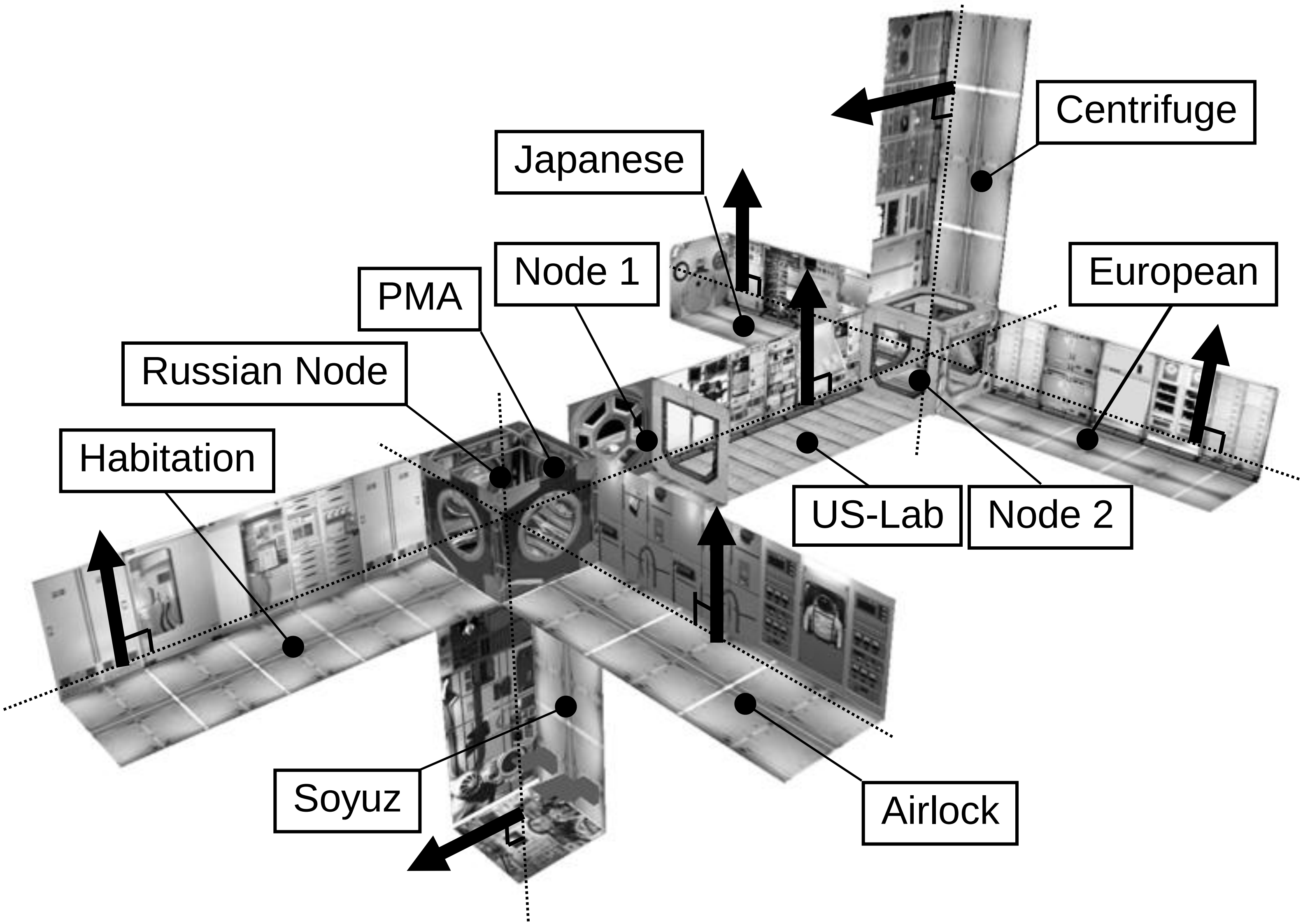

Centrifuge
Japanese
Node 1
European
PMA
Russian Node
Habitation
US-Lab
Node 2
Soyuz
Airlock

Figure 2

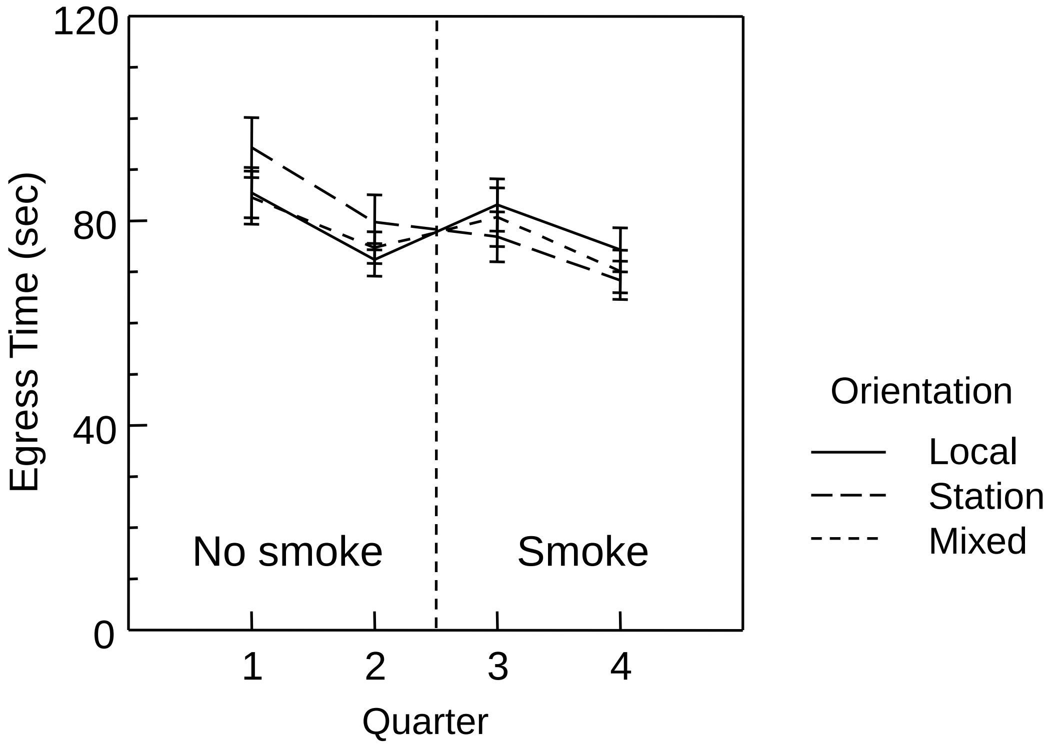

120
80
40
0
Egress Time (sec)
No smoke
Smoke
1
2
3
4
Quarter
Orientation
Local
Station
Mixed

Figure 3

Click here to download Figures (separate file for each): Aoki_Figure3_Rev.pdf

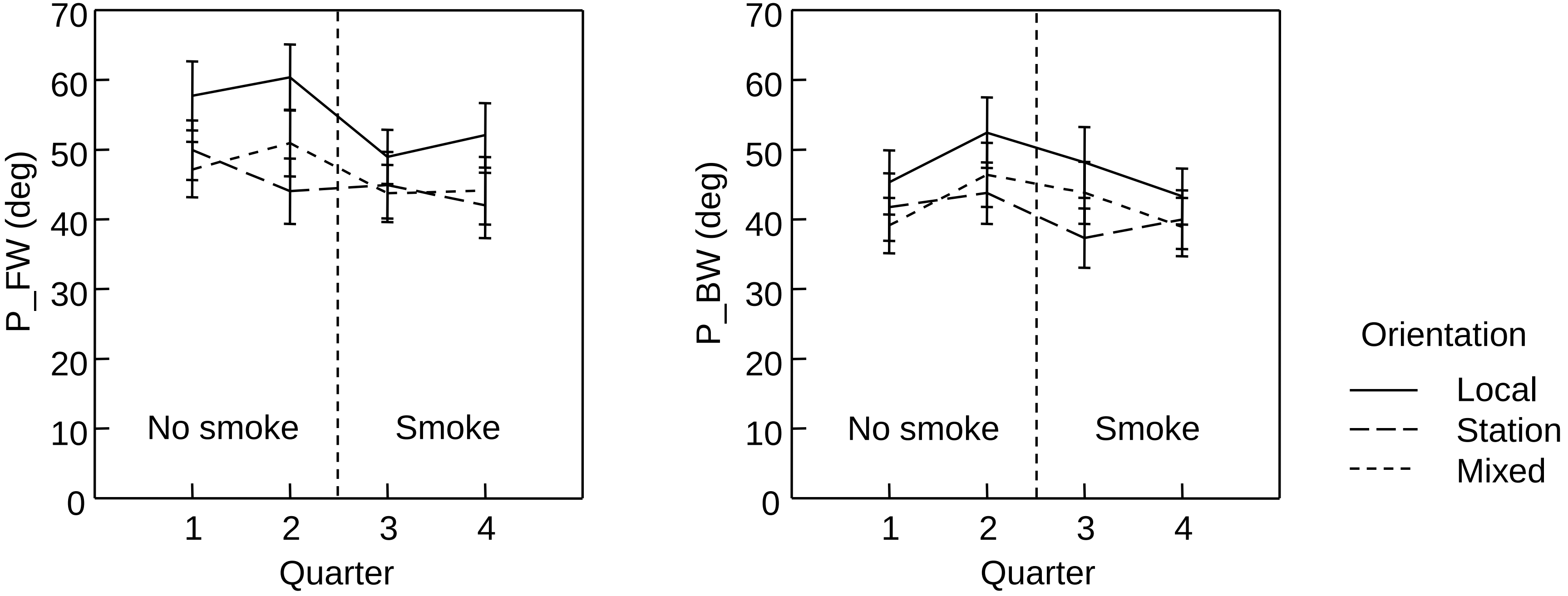
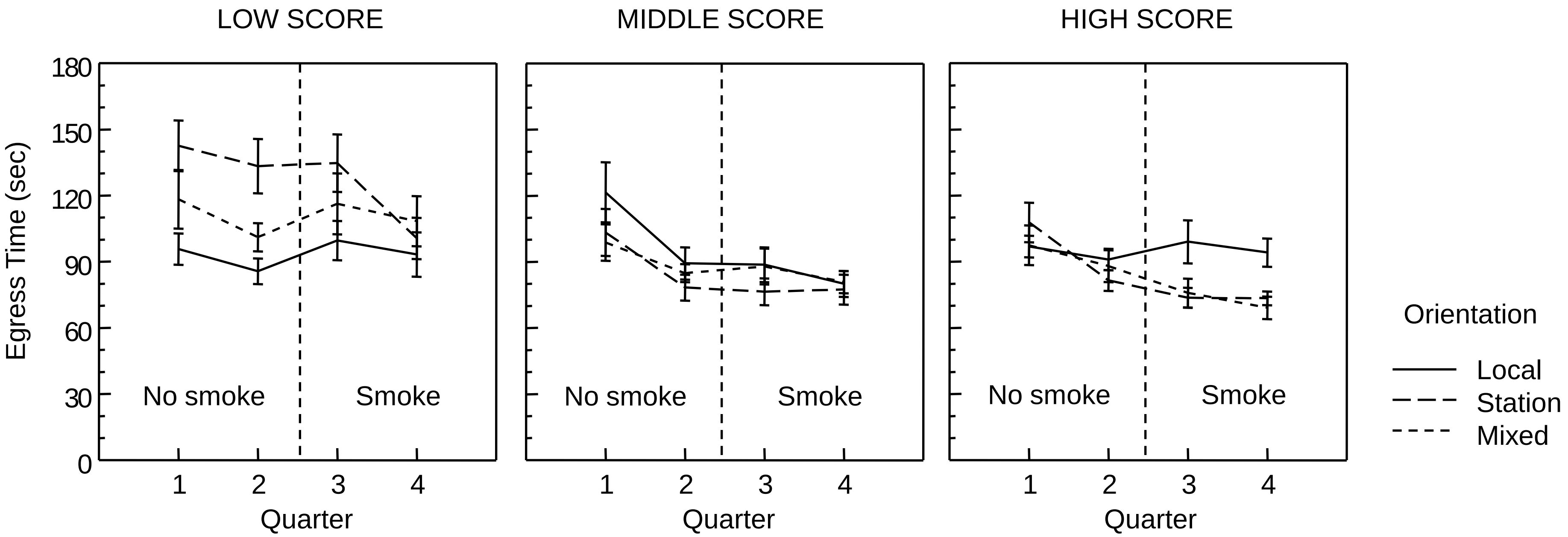


Figure 4


LOW SCORE
MIDDLE SCORE
HIGH SCORE
Egress Time (sec)
180
150
120
90
60
30
0
No smoke
Smoke
1
2
3
4
Quarter
Orientation
Local
Station
Mixed