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Aircraft Evacuations Through Type-III Exits II: Effects of Individual Subject Differences

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16. Abstract

INTRODUCTION. Simulated emergency egress from Type III over-wing exits was studied to support regulatory action by the FAA. Passageway width from the aircraft center aisle to the Type-III exit was the major variable of interest; effects of individual subject attributes on egress were analyzed to determine whether such variables should be better controlled in future research. Effects of subject evacuation experience were also analyzed to account for unexpected anomalies found for age-group egress performance. METHODS. Two subject groups of differing mean ages were employed in a repeated-measures evaluation of different passageway widths leading to the exit in the CAMI aircraft cabin evacuation facility. Main effects of passageway width on egress rates were determined using analysis of variance; individual subject age, weight, height, gender and waist-size were then subjected to multivariate analysis of variance and stepwise regression analysis to assess the effects of these within-subjects factors. Repeated measures analyses of evacuations at individual passageway widths also provided information about effects of evacuation experience for individual subjects. RESULTS. Main effects were found for passageway width ($p < .01$) and subject age ($p < .00001$), weight ($p < .0004$), waist size ($p < .0015$) and gender ($p < .001$). The stepwise regression analysis showed that individual subject age accounted for the largest amount of experimental variance (43%), followed next by weight, waistline size (which correlated .89 with weight), and gender. Evacuation experience was found to enhance evacuations by allowing older subjects to develop better egress strategies and correct inefficient egress techniques. CONCLUSION. Studies of emergency aircraft evacuations should account for the personal characteristics of the individuals employed in the research, as physical attributes such as age, weight, and gender may significantly affect the results, and can be varied systematically to address certain research questions more appropriately. Similarly, research studies employing repeated-measures designs can be affected by the evacuation experience subjects acquire; such studies should control for these effects to prevent the possibility of confounded results.

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INTRODUCTION

The ability of passengers to evacuate an aircraft in an emergency is dependent on many variables. In recognition of this principle, the Federal Aviation Administration (FAA) has established several Federal Aviation Regulations (FAR) to assure that transport category aircraft are designed, manufactured, and operated in a manner that provides passengers an optimum emergency evacuation capability. Regulations that address the emergency evacuation capability of transport category aircraft include Section 25.807, *Emergency exits*; Section 25.809, *Emergency exit arrangement;* Section 25.810, *Emergency egress assist means and escape routes;* Section 25.811, *Emergency exit marking;* and Section 25.813, *Emergency exit access.* Each of these rules is specified in terms of the minimum criteria necessary for compliance; combined, these FARs provide for initial indications that transport category aircraft are designed to provide sufficient evacuation capability to comply with Section 25.803, *Emergency evacuation,* the so-called 90 second rule.

Section 25.803 requires that, to be certificated under Section part 25, any type of transport category aircraft with a seating capacity greater than 44 passsengers must be shown to be capable of evacuating its maximum seating capacity (including crewmembers) from the airplane to the ground in 90 seconds or less. FAR part 25, Appendix J, specifies the demonstration criteria and procedures to be used for showing compliance with this rule; *Advisory Circular* (AC) 25.803 provides further clarifications of how the demonstration(s) should be conducted.

Within both Section part 25, Appendix J, and AC 25.803, there are also various criteria related to the aircraft, the crewmembers, and, importantly, the passengers used in the demonstration The passenger characteristics are supposed to represent the *normal* for passengers flying on transport category aircraft; the criteria for such passengers include requirements for normal health and what is commonly known as the representative *age/gender mix.* The demonstration criteria for age/gender mix detail the percentage of female passengers required, as well as what percentage of (female) passengers must be over 50 years of age.

The specific criteria for the age/gender mix are included because differences in passenger agility and speed may have important effects on the outcome of the certification demonstration conducted pursuant to Section 25.803. Although it is well known that general decreases in agility and speed accompany increases in age, and that females tend to be slower and less agile than aged-matched males, the extent to which such attributes affect aircraft evacuations has received little attention. In a study of passageway-width effects on aircraft evacuations through a Type-III overwing exit, McLean, George, Chittum & Funkhouser (1995) found that evacuations were slower for an older group of subjects. Muir, Bottomley & Hall (1992) also found that, when a monetary reward for speed was offered to a fixed percentage of subjects evacuating through a Type-III exit, a proportionalely larger number of the subjects who received the reward were male. These studies were not directed at detecting individual subject differences in evacuation efficacy, but the findings do suggest that emergency aircraft evacuations are affected by the general reductions in speed and agility recognized with advanced age, and for women.

To better understand the effects of such passenger variables on aircraft evacuations, the age, weight, height, waist size, and gender of the subjects employed in the McLean, et al., (1995), Type-III exit study were analyzed for their effects on evacuation performance. Specifically, each of the variables was analyzed individually, and in combination with the others, for its effect on the ability

of subjects to traverse the Type-III passageway/exit-opening. Then the relative contribution of each subject variable to evacuation performance was determined.

METHODS

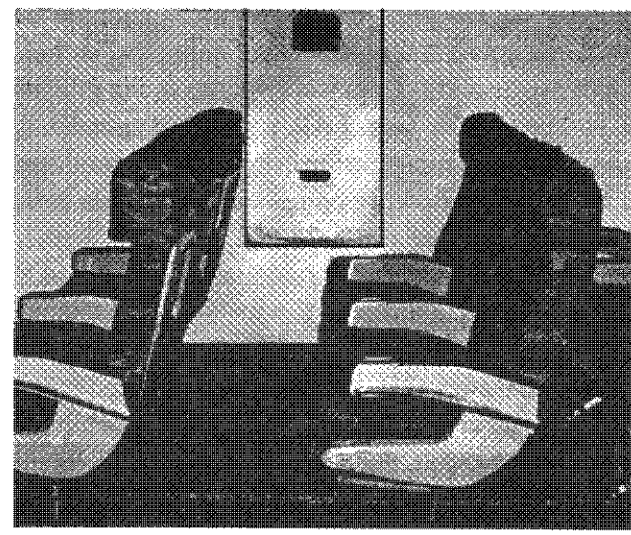
SUBJECTS: Two groups of 37 subjects were employed in the study. The groups were roughly matched on weight and height, with nearly equal gender representation; subject age was the primary grouping factor. Group 1 subjects ranged in age from 18 to 40 years (mean = 27 yrs), whereas Group 2 participants were between 40 and 62 years old (mean = 47 yrs). Subject experience with transport category airplanes and information about emergency evacuation procedures were controlled by allowing subjects to learn how to climb through the Type-III exit at the beginning of each group's participation.

DESIGN: Both groups of subjects completed a series of simulated emergency evacuations using a Type-III exit (Figure 1) approached via 5 different passageway widths (6, 10, 13, 15 & 20 inches) and 3 seat encroachment distances (a 5-inch minimum, a 10-inch midpoint, and a 15-inch maximum) in a counter-balanced design. Each trial series required 3 consecutive mornings for each group to complete the total of 30 trials. The trial series began with the learning exercise, which was accomplished with the seat assemblies adjacent to the Type-III exit removed. Using this configuration, subjects were allowed to climb through the exit opening, learning how to do it as quickly as possible. After only 2 such trials for each group, the subjects were performing as well as to be expected (based on a previous pilot study). The experimental series was then begun; two trials were conducted at each passageway width and encroachment distance before the aircraft interior was changed to a new configuration.

MOTIVATION: To encourage an optimum level of subject performance throughout the study, a "competitive cooperation" was established among subjects to serve as a motivational mechanism. Subjects were instructed that a bonus (unspecified) would be paid to the top 3 performers in the group, i.e., those who had the fastest mean individual egress times across all trials. Subjects were required to sit at a different location on every trial to counterbalance seat/exit proximity effects. Subjects were also instructed that they could not jump ahead in the egress queue, shove other subjects out of the way, or impede other subjects in any way. The key to success, they were told, was to be as individually fast as possible by helping their fellow subjects to be as fast as they could. In addition to this motivational technique, two actual flight attendants participated in the evacuation trials to further maintain high levels of motivation and effective egress. Of these, one flight attendant was stationed at the rear of the cabin to urge subjects forward, while the other one was placed in the outboard seat in the row just ahead of the Type-III exit. At the start of a trial, this flight attendant would stand up, turn around, and offer encouragement to subjects during their egress.

PROCEDURE: Subjects began each trial sitting in six-abreast seat assemblies located both forward (40%) and aft (60%) of the single starboard Type-III exit, which was the only egress route available. A buzzer was used to signal the start of the trial,

Figure 1
Typical Type-III Exit



whereupon the Type-III exit cover was immediately removed from outside the aircraft simulator by a research confederate. Egress was timed and archived using videotape imprinted with time codes. At the conclusion of a trial, subjects were assembled outside the aircraft simulator for about 10 minutes to await the reconfiguration of seat assemblies to form a different passageway width and encroachment distance, after which they re-entered the simulator for another trial.

Evacuation times for each trial were manually extracted from the videotapes, gathering both the total group evacuation times and individual subject *passageway/exit-opening negotiation times* as the dependent variables. Analyses of the total group evacuation times indicated that there were no nonlinearities or dissimilarities between analogous data from both groups of subjects which would invalidate combining them for analyses of the effects of individual subject differences on egress. These analyses were conducted using *SPSS for Windows®*, Release 6.0.

RESULTS

The results obtained from both groups were consistent across trials, showing increases in evacuation times related to both narrower passageway widths and larger seat encroachment distances (Figures 2 & 3), without systematic effects that could be ascribed to either experience, fatigue, and/or changes in motivation level. The 3-way (passageway width x encroachment distance x subject group) analysis of variance (ANOVA) revealed main effects of passageway width ($p<.001$), seat encroachment distance ($p<.001$), and subject group ($p<.001$) without significant interactions between any of the variables. A 2-way (passageway-width x encroachment distance) repeated measures ANOVA on the younger group data showed effects of passageway width ($p<.001$) and encroachment distance ($p<.03$); Duncan's Multiple Range Tests (for discussion, see Winer, 1962) isolated the passageway-width effects to the 10-inch and smaller configurations and the encroachment distance effects to the maximum

Figure 2
MAIN EFFECT OF PASSAGEWAY WIDTH
On Total Evacuation Times for Each Group
(At the minimum encroachment for each passageway width)

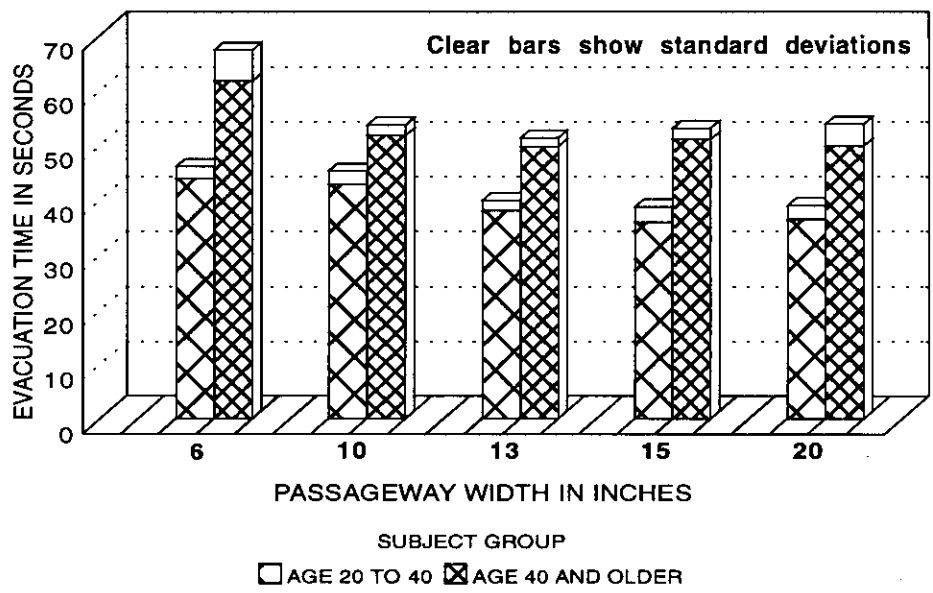


Figure 3

MAIN EFFECT OF ENCROACHMENT
On Total Evacuation Times for Each Group
(Across all passageway widths)

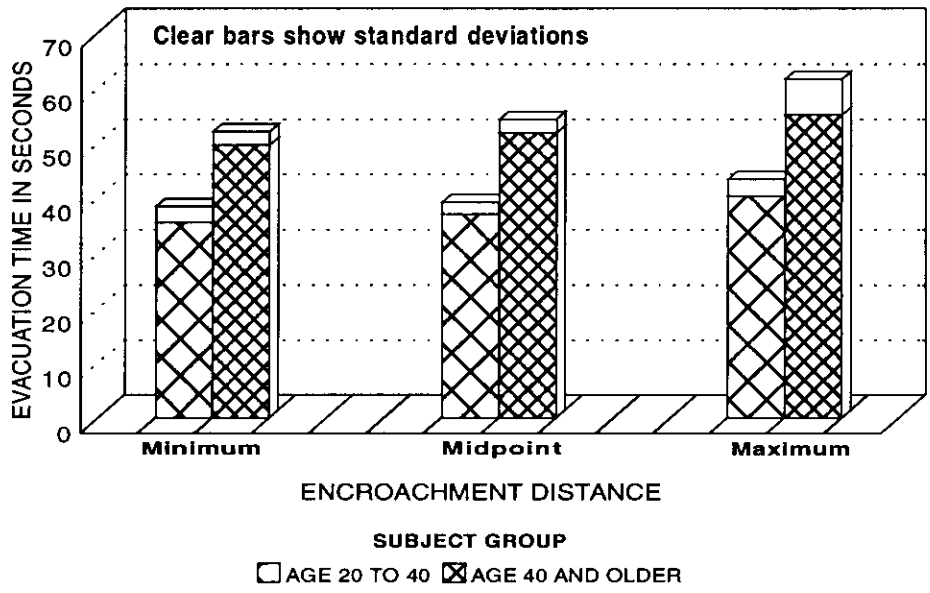


Figure 4

Effects of Age
on Individual Egress through Type-III Exits

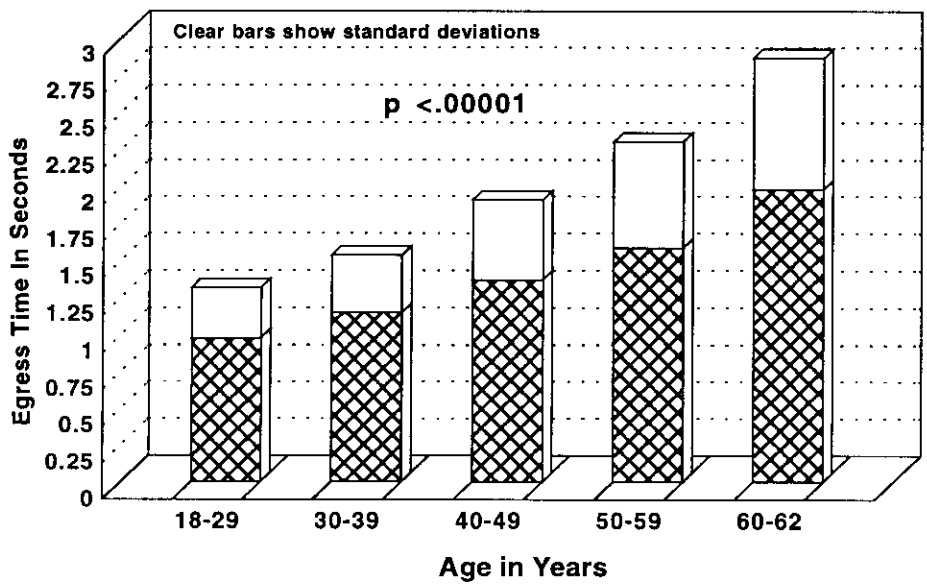


Figure 5

Effects of Weight
on Individual Egress through Type-III Exits

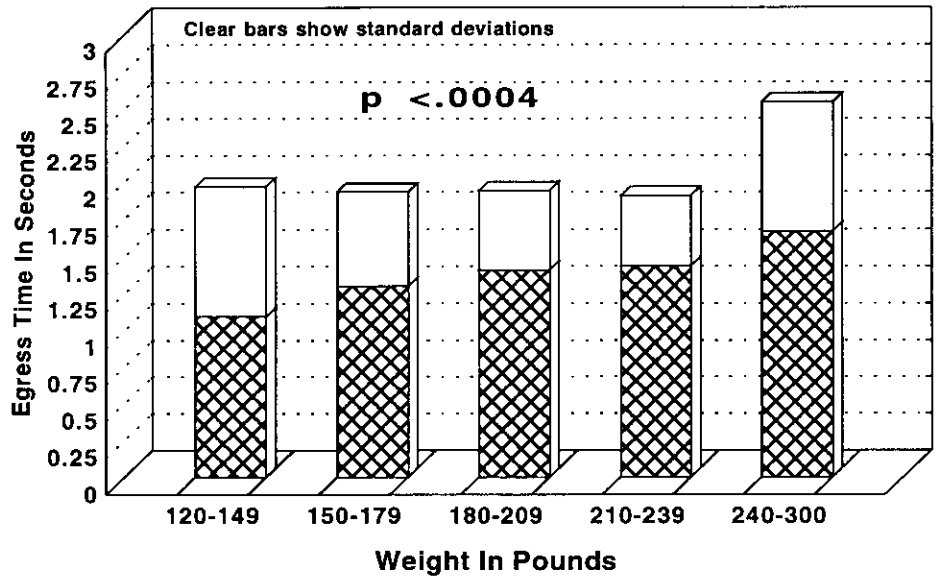


Figure 6

Effects of Waist Size
on Individual Egress through Type-III Exits

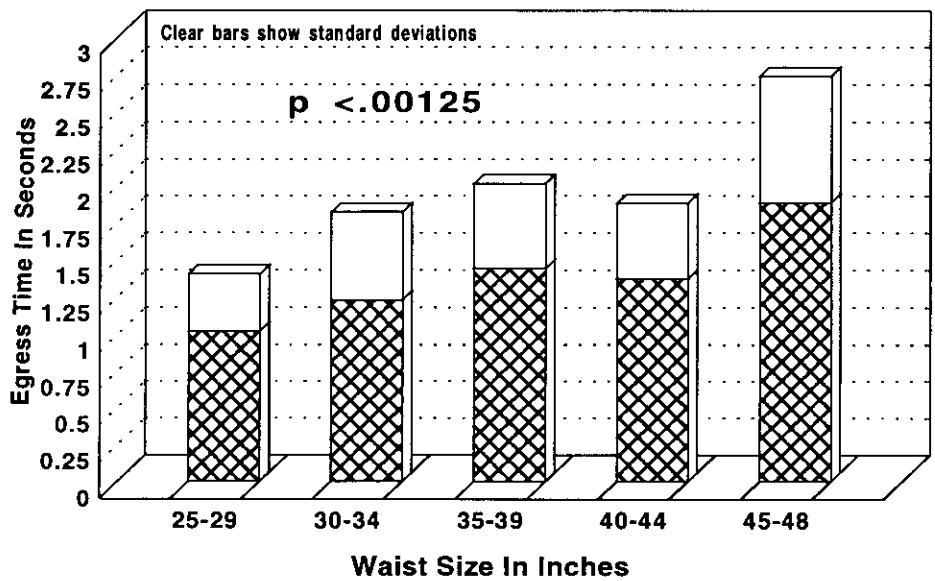


Figure 7

Effects of Gender
on Individual Egress through Type-III Exits

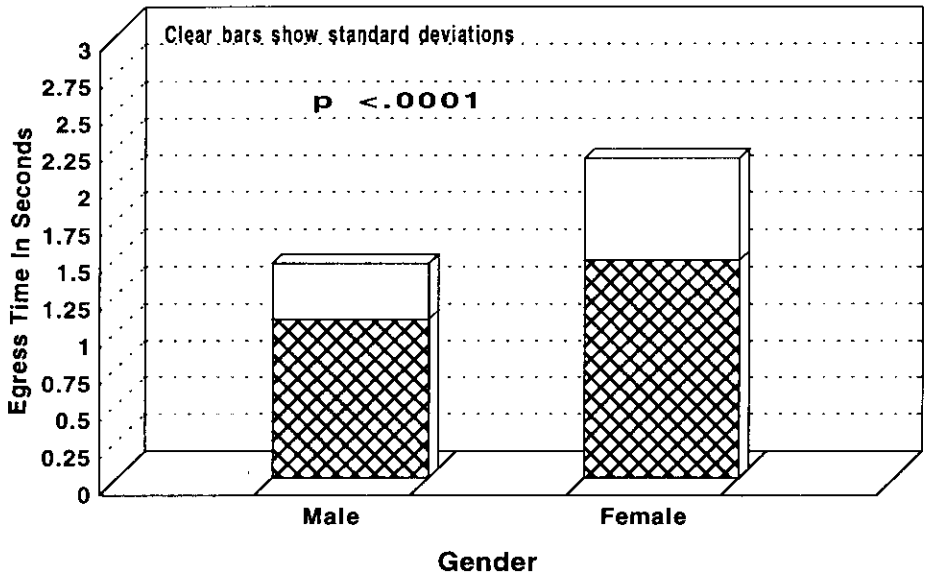
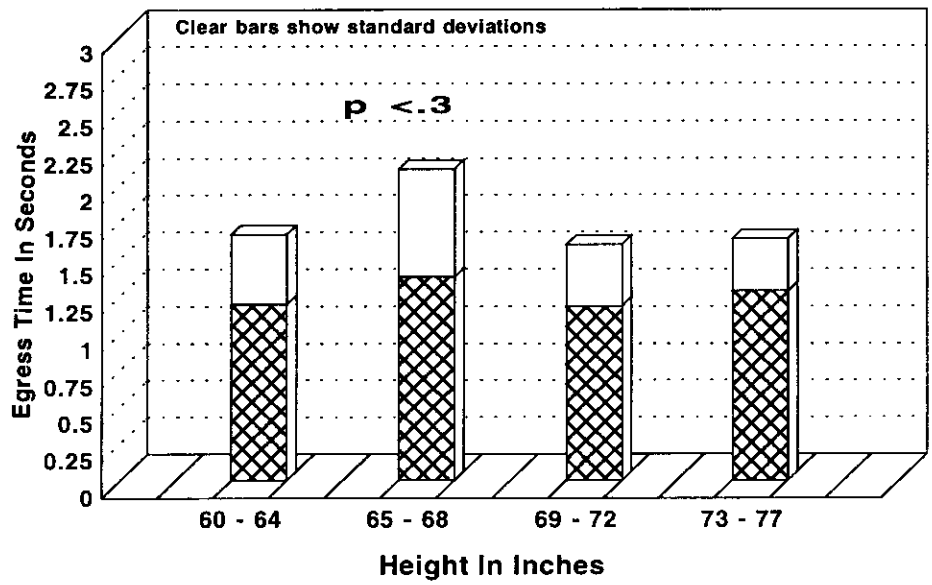


Figure 8

Effects of Height
on Individual Egress through Type-III Exits



encroachment distance. A similar ANOVA on the older group data found an effect of passageway width ($p<.025$) without an effect of encroachment distance. The Duncan's Test on passageway-width showed the effect to be limited to the 6-inch passageway width. This limited passageway-width effect (relative to the younger group) apparently resulted from an inadvertent change in instruction set given the older group for the 10-inch width (see McLean, et al., 1995, for discussion). Importantly for the individual subject attribute analyses, interaction effects for both group by passageway width ($p<.14$) and group by encroachment distance ($p<.96$) were statistically insignificant, suggesting that subject attribute data from these groups could be combined without violating the assumptions of the statistical model.

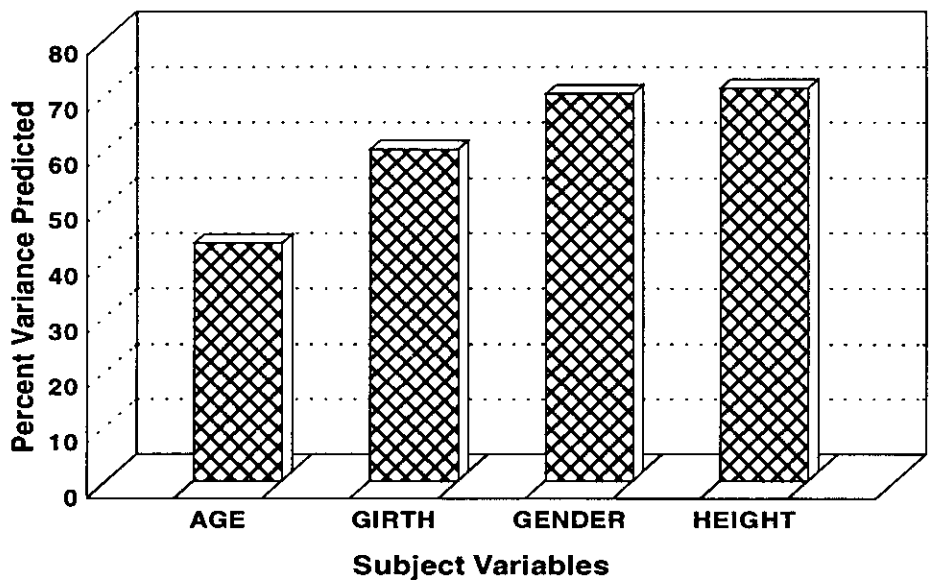
Accordingly, a composite data set was created, combining the individual attributes for each subject in both groups and the individual Type-III passageway/exit-opening negotiation times, to study the effects of the individual subject attributes on egress. This composite data set contained over 2,000 individual observations. A multivariate analysis of variance (MANOVA) was conducted, using the mean subject egress times at each Type-III passageway/exit-opening; subject age, weight, waist size, height, gender, and aircraft configuration (passageway width/encroachment distance) were the independent variables. This MANOVA confirmed main effects for age ($p<.00001$), weight ($p<.0004$), waist size ($p<.00125$), and gender ($p<.0001$), but not height ($p<.3$). There were no significant interaction effects of any of the subject variables with aircraft configuration. Figures 4 through 8 display these subject attribute effects.

A stepwise multiple regression analysis revealed that, of the individual subject attributes investigated, age accounted for the largest amount (43%) of experimental variance produced; the residuals were weight/waistline (girth), gender, and height, in decreasing order of influence (see Figure 9).

In addition to establishing the effects of the subject attributes on mean subject egress times, a second set of analyses was conducted in response to a lingering question posed by the group evacuation findings in the McLean, et al. (1995), Type-III exit study. There it was noted that although the older

Figure 9

Cumulative Stepwise Effects
of Individual Subject Variables



subject group generally performed more slowly, there was little indication of a hyperadditive (synergistic) interaction effect produced by progressive age-related decrements in agility combined with minimal passageway widths and/or greater seat encroachment distances. This lack of a differential, age-based effect on evacuation performance was hypothesized to result from the training/learning regimen the subjects were provided before the experimental series began, and was thought to depend on one of two possibilities: 1) learning the behavioral requirements of using the Type-III exit enhanced the physical efficiency (skill) of the older subjects, and/or 2) enhanced knowledge about the requirements for egress through the Type-III exit allowed them to develop strategies that masked any effect of progressive, age-related decrements in agility.

Recall that after the training/learning regimen was concluded, subjects were required to egress 2 times at each passageway width. It was hypothesized that by comparing the data from each of these trials, an answer might be forthcoming to determine which, if either, of the explanations was correct. First, the data were classified by passageway width at the minimum encroachment distance for each width, egress trial, and subject age (grouped by decade as depicted in Figure 4) to visually identify the potential for subject age by passageway width by egress trial interaction effects (see Figures 10-14). After identifying that the 6- and 10- inch passageway widths exhibited potential interaction effects for 50-year and older subjects, a two-way (age x passageway width) ANOVA was conducted on the trial-1 minus trial-2 difference scores for individual subject egress times to explore more discretely the effects of subject age on egress times at each passageway width for each trial. This analysis was designed to characterize the subject age by passageway width by egress experience interaction effect, using the specialized (trial-1 minus trial-2) experience at each passageway width to begin differentiating between the competing explanations. It confirmed a general effect on subject egress times of age by egress trial ($p<.015$) and a differential effect of subject age by passageway width by egress

Figure 10

Effects of Age And Egress Trial
on Individual Subject Egress Using the 6-Inch Passageway

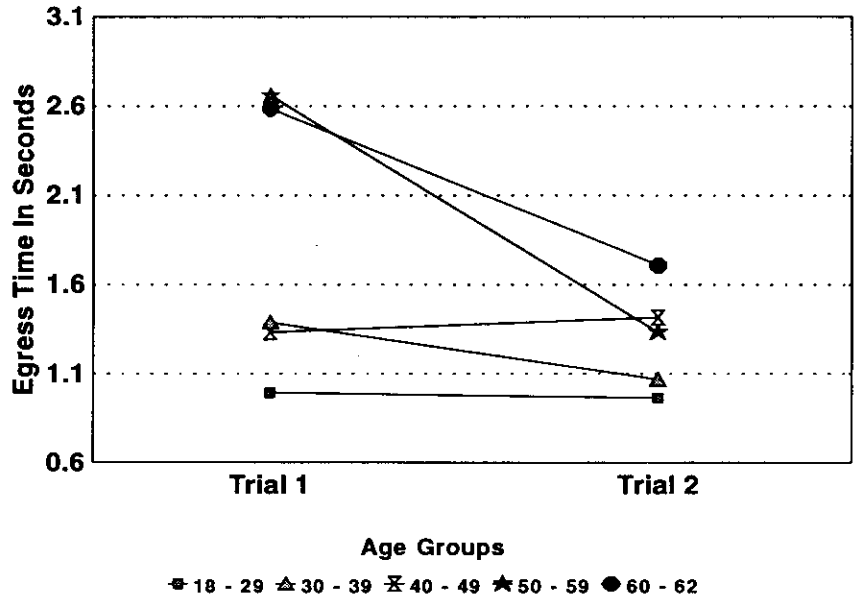


Figure 11

Effects of Age and Egress Trial
on Individual Subject Egress Using the 10-Inch Passageway

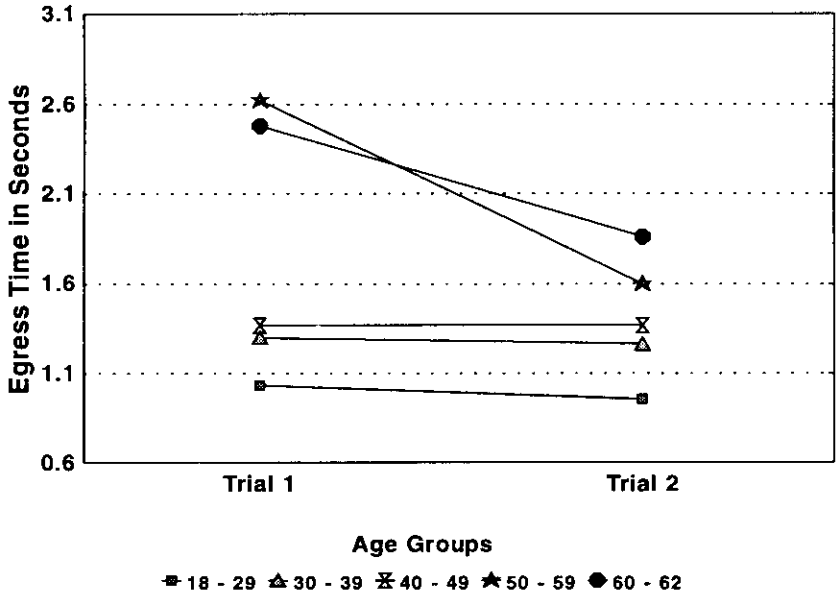


Figure 12

Effects of Age and Egress Trial
on Individual Subject Egress Using the 13-Inch Passageway

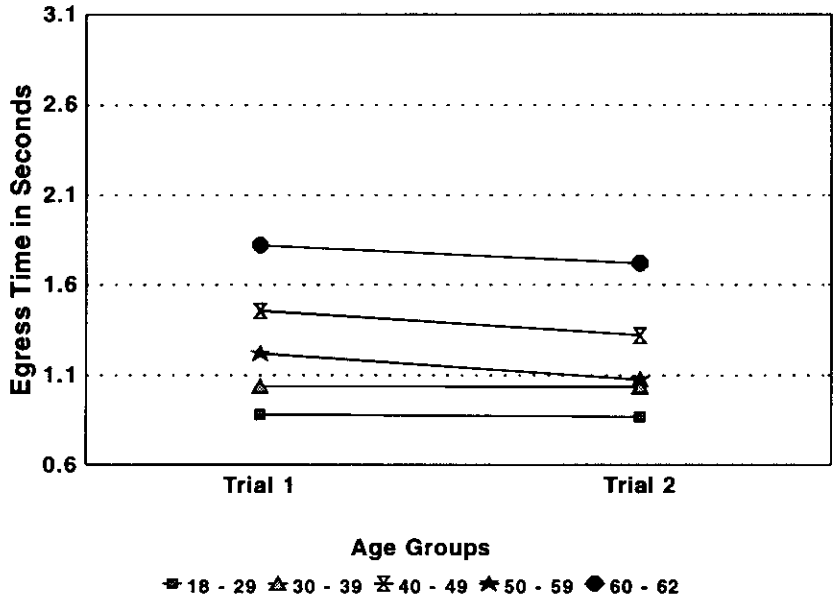


Figure 13

Effects of Age and Egress Trial
on Individual Subject Egress Using the 15-Inch Passageway

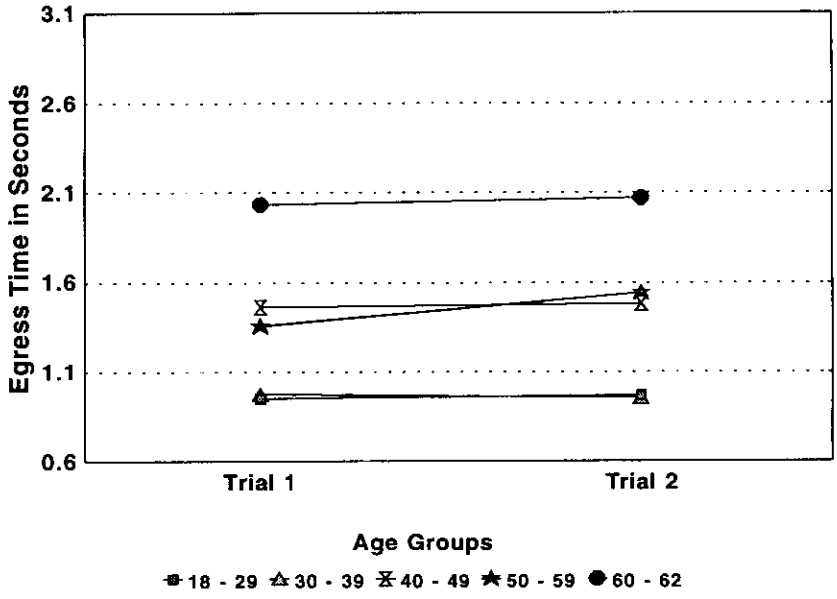
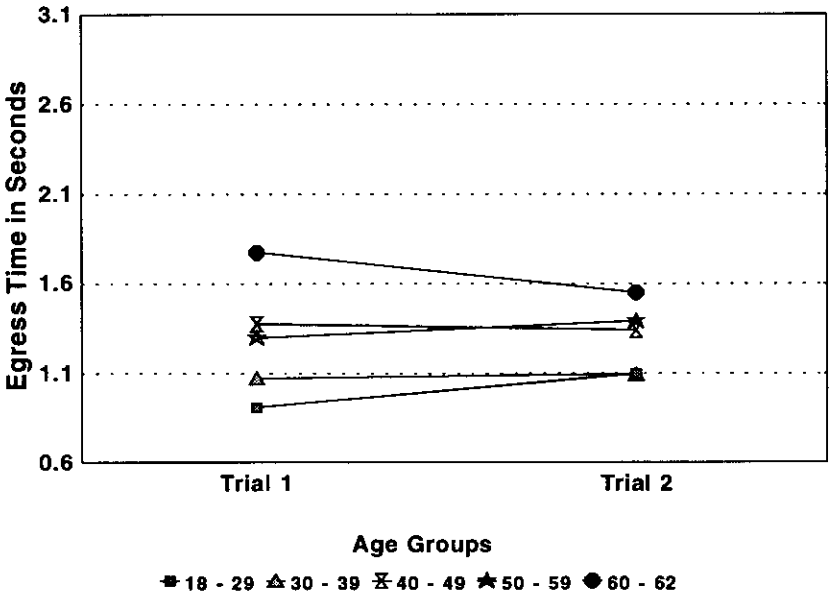


Figure 14

Effects of Age and Egress Trial
on Individual Subject Egress Using the 20-Inch Passageway



trial (p<.002; see Figure 15). Two-way (age x passageway width) ANOVAs were then conducted on the data from egress trials 1 and 2 to identify the effects of generalized versus specialized egress experience. Comparisons of trial-1 egress times for each subject age group at each passageway width yielded main effects of subject age (p<.001) and passageway width (p<.001), and an age by passageway width interaction effect (p<.02; see Figure 16), but the only effect found for trial-2 egress was produced by subject age (p<.001). The insignificant trial-2 age by passageway width interaction effect (p<.9) may be seen in Figure 17.

Using the same subject age groupings and classifying the data from trials 1 and 2 by seat encroachment distance, graphs were prepared to allow visualization of the subject age by seat encroachment distance interaction (Figures 18-20). Then a two-way (subject age x encroachment distance) ANOVA was conducted on the trial-1 minus trial-2 individual subject egress time difference scores to characterize the subject age by encroachment distance by egress experience interaction effect in a manner analogous to that employed with the passageway widths. This analysis confirmed the general effect on subject egress times of subject age by egress trial (p<.02) and a differential interaction effect of subject age by encroachment distance by egress trial (p<.002; see Figure 21). The 2-way (age x encroachment distance) ANOVA conducted on the data from egress trial 1 also revealed a main effect of age (p<.001) and an age by encroachment distance interaction effect (p<.002; see Figure 22). Only the main effect of subject age was significant for the egress trial 2 (p<.001). The trial-2 age by encroachment distance interaction effect failed to achieve statistical significance (p<.8; see Figure 23).

Similar analyses were conducted on all the other subject attributes in combination with passageway widths and encroachment distances; no systematic effects were found for any of these variables.

Figure 15

Age By Passageway Width Effects
on Trial 1 Minus Trial 2 Difference Scores

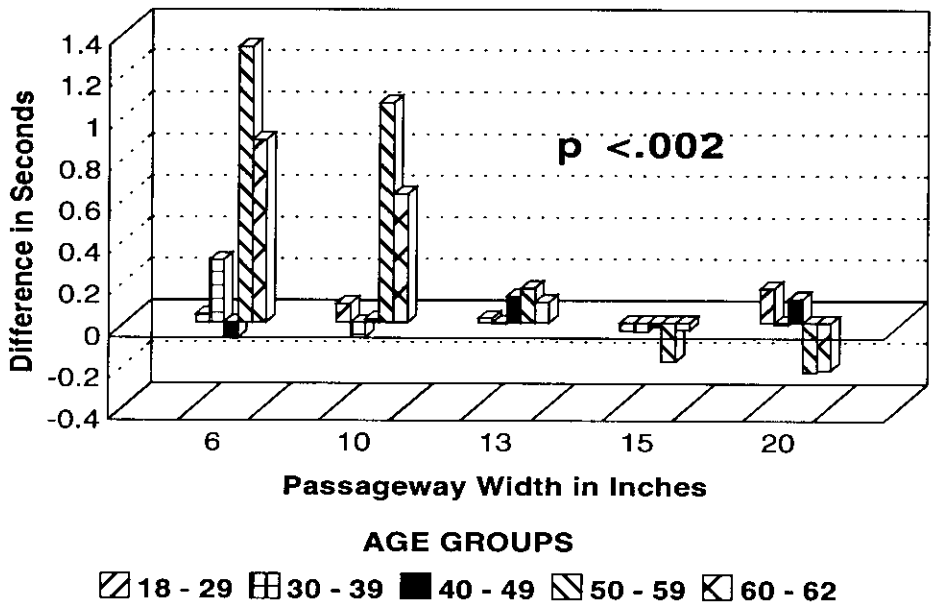


Figure 16

Effects of Age and Passageway Width
on Individual Subject Egress In Trial 1

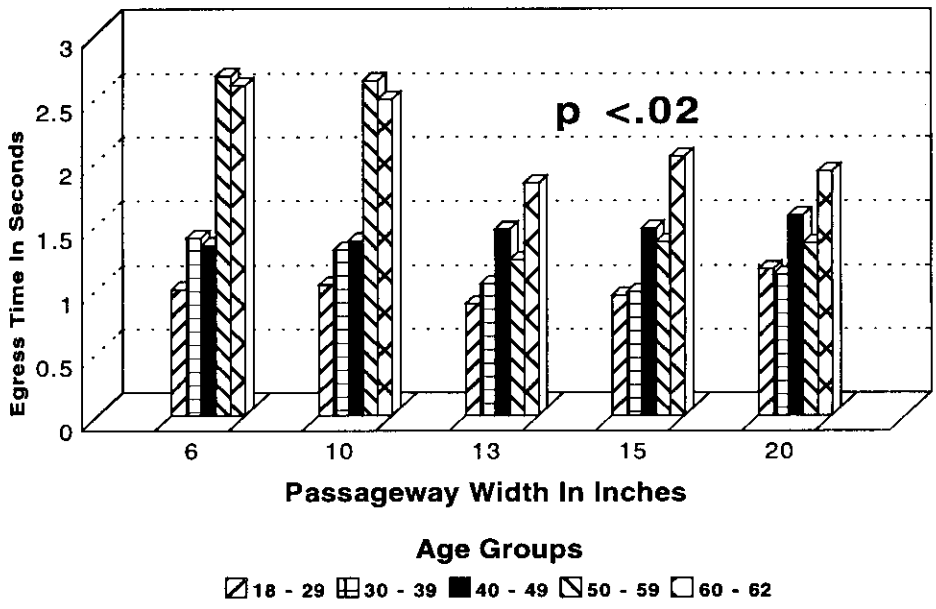


Figure 17

Effects of Age and Passageway Width
on Individual Subject Egress In Trial 2

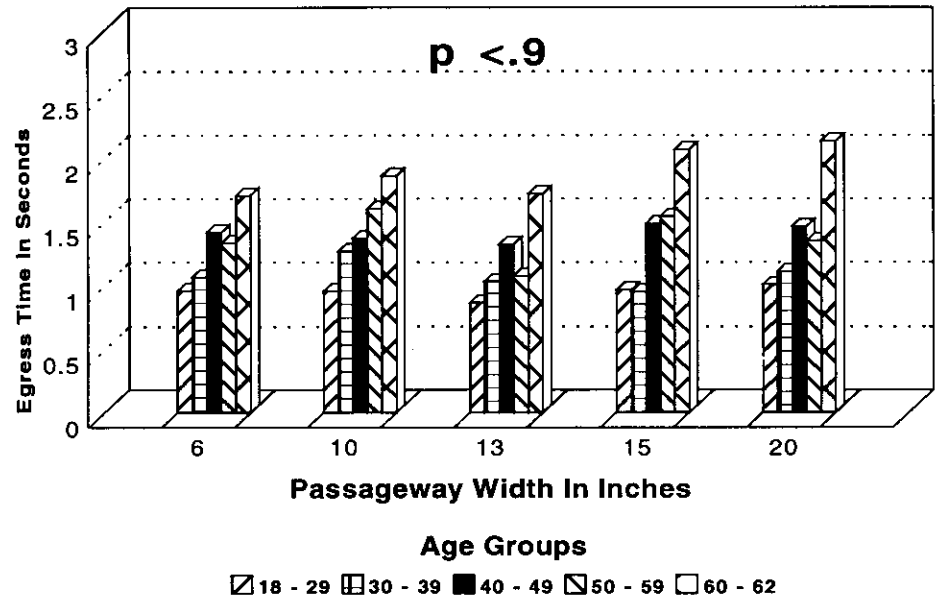


Figure 18

Effects of Age And Egress Trial

on Individual Subject Egress Using the Minimum Encroachment

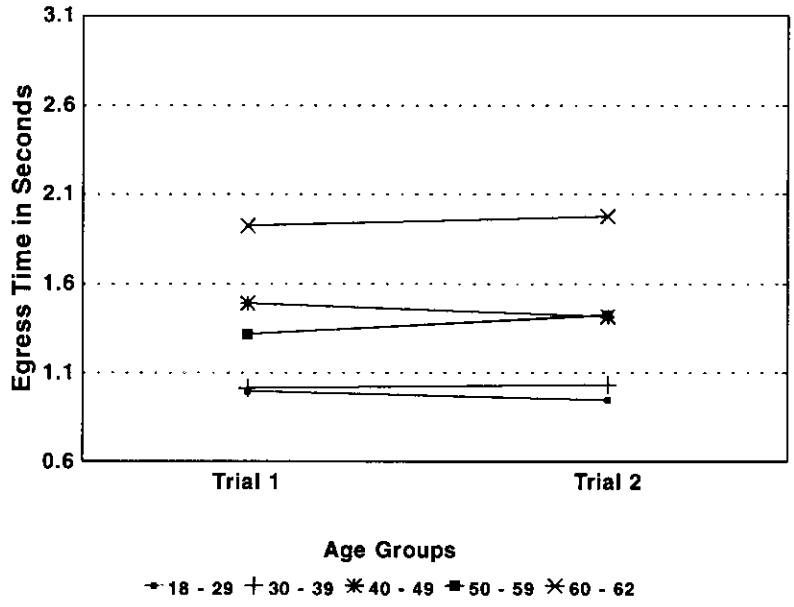


Figure 19

Effects of Age And Egress Trial

on Individual Subject Egress Using the Midpoint Encroachment

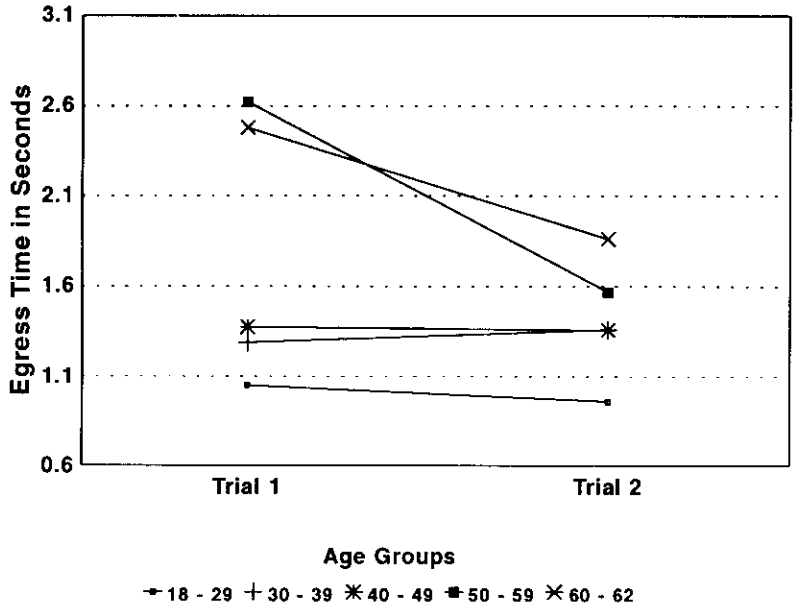


Figure 20

Effects of Age And Egress Trial

on Individual Subject Egress Using the Maximum Encroachment

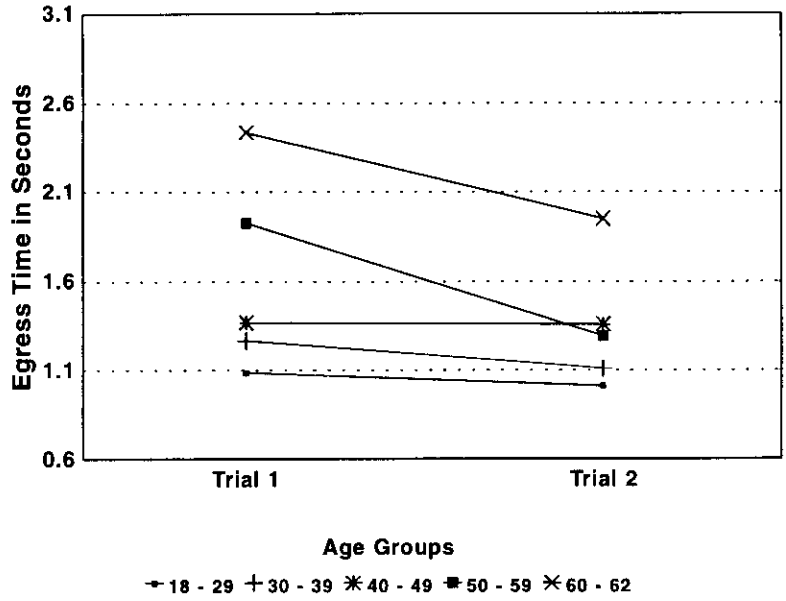


Figure 21

Age By Encroachment Distance Effects

on Trial 1 Minus Trial 2 Difference Scores

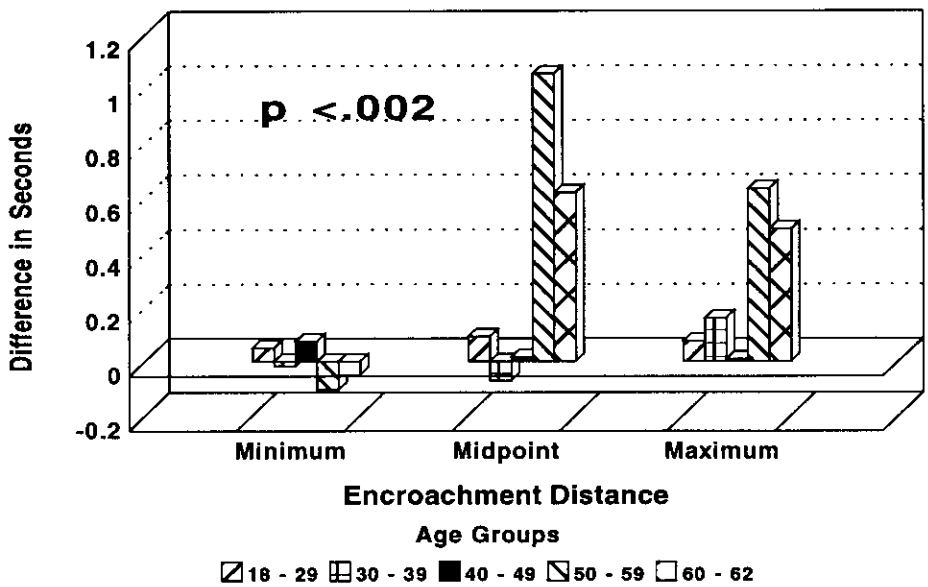


Figure 22

Effects of Age and Encroachment Distance
on Individual Subject Egress In Trial 1

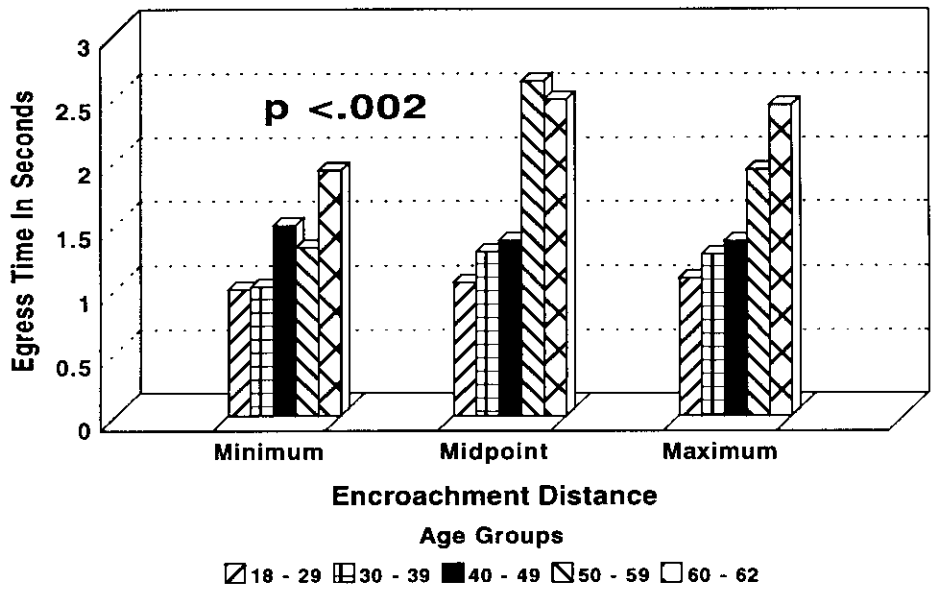
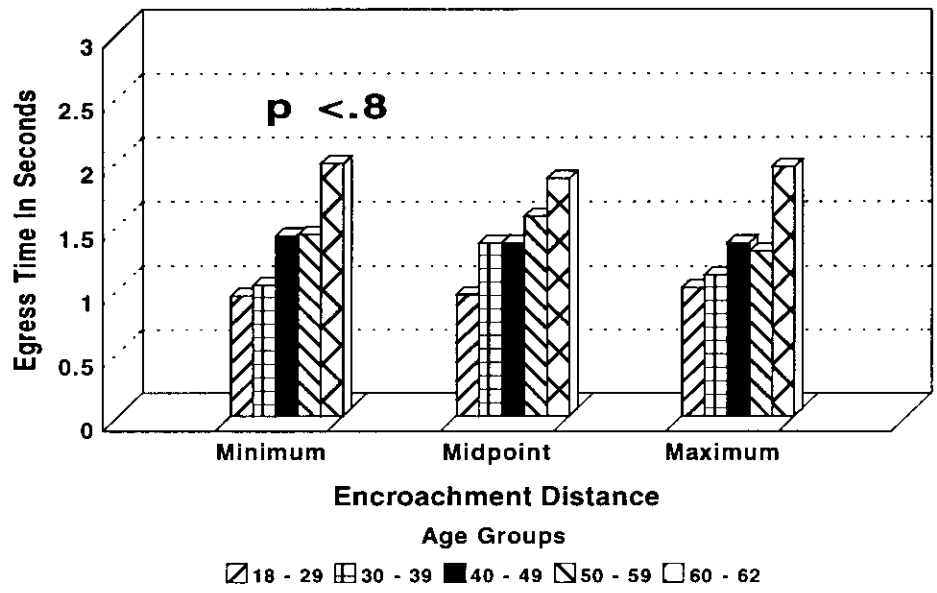


Figure 23

Effects of Age and Encroachment Distance
on Individual Subject Egress In Trial 2



DISCUSSION

The ability of subjects to evacuate an aircraft through Type III overwing exits has been shown to depend upon several factors. In addition to aircraft interior configuration, increases in subject age and weight were associated with nearly linear increases in subject egress times, and subject waist size was seen to be the functional equivalent of subject weight in delaying egress. Gender also proved to be an important variable in determining speed of egress, as females were much slower than males. These effects appear to result from the decrements in agility produced as humans become older, heavier, and wider, as well as the general case of reduced agility for females relative to males. Unexpectedly, none of the subject variables was shown to interact hyperadditively with passageway width and/or seat encroachment distance; this result seemed counterintuitive to the proposition that significantly narrower, or more offset, passageways should produce multiplicative problems for the less agile subjects. Increases in subject height had also been hypothesized to affect speed of egress in the same manner as age and weight, because of the small (36") vertical dimension of the Type III exit opening. However, this did not prove to be the case, probably because the overhead stowage bins caused tall subjects to bend at the entrance to the passageway well ahead of the exit opening, and thereby organize their egress behavior to overcome any adverse ergonomic effects of significantly greater than average stature. Together, these results indicate that egress through the Type-III exit opening requires significant agility, and that individual subject attributes play as big a part in effective egress as does aircraft configuration.

The failure to find a hyperadditive interaction of age with aircraft interior configuration had been noted in the earlier McLean, et al., (1995) study. The authors hypothesized that the training/learning regimen that subjects had been provided prior to the experimental series could have been responsible, resulting in an ability of older subjects to profit differentially from the egress experience to mask synergistic effects of advancing age and more restrictive interior configurations. This effect was further hypothesized to depend on either a generalized performance improvement, in which older subjects became more skillful at exiting through the Type-III exit, and/or a strategic learning effect by which familiarity with a specific aircraft configuration allowed older subjects to correct an inefficient egress technique.

The results depicted in figure 15 provide the definitive answer. This graph shows that, when using egress trial difference scores and subjects grouped by 10-year age intervals (rather than above and below 40 years old), the significant interaction of age and passageway width is readily perceived. As in the original results shown in figures 2 & 3, subjects generally performed more slowly with advancing age; but 50-year and older subjects performed comparatively more slowly at the 6-inch and 10-inch passageways on trial 1, as indicated by the large positive difference scores at these passageway widths. This subject age by passageway width by egress trial interaction effect was found to be significant ($p<.002$), and provides the basis to resolve which learning effect was responsible for eliminating the age by aircraft configuration interaction effect.

Recall that, after the training/learning regimen, subjects were performing asymptotically when the trials began. Also recall that the trial order was counterbalanced by passageway width, that two egress trials were performed at each passageway width, and that within this design, the 6- and 10-inch passageways were the last two widths to be traversed. In spite of the earlier experience, the age by passageway width interaction effect indicated that 50-year and older subjects performed significantly slower at the 6- and 10- inch passageway widths on trial 1 ($p<.02$), but had improved their performances significantly on trial 2, as the interaction effect was no longer significant ($p<.9$). Had a generalized performance improvement been responsible for the failure to find a hyperadditive interaction effect using the mean egress times, this differrence in egress times at the narrower passageway widths on trial 1 should not have been found.

As the difference in egress times for the narrower passageways had been overcome on trial 2, this indicates that a more specialized effect of egress experience had been established, whereby the older subjects were able to devise a better strategy than the first one they had used. Returning to figures 10 through 14, it can be seen that the 49-year and younger subjects performed much better, and essentially alike, on both trials for all the passageway widths, suggesting a "floor effect" beyond which they could improve their performances very little, if any.

The similarity of effects for seat encroachment distance supports this interpretation. Figure 21 depicts the difference in subject egress times at each encroachment distance for trial 1 minus trial 2 for each of the 5 age groups. There it can be seen that all the subjects performed essentially alike on both trials at the minimum encroachment distance, but the 50-year and older subjects were again able to improve their performances on the second trial at the more restrictive encroachment distances. The analysis of trial-1 minus trial-2 difference scores for individual subject egress times found the subject age by seat encroachment distance by egress trial interaction to be significant ($p<.002$). This result once more indicates that a specialized effect of egress experience was in effect. The age by encroachment distance interaction effects in the individual ANOVAs for trials 1 and 2 confirm that 50-year and older subjects were significantly slower at the midpoint and maximum encroachment distances on trial 1 ($p<.002$), but were able to improve their performances on trial 2, as the interaction effect failed to achieve significance ($p<.8$). The apparent "floor effect" that precluded improved performance was again in evidence for the 49-year and younger subjects.

The implications of these results for regulatory concerns are several. First, the requirements for an *age/gender mix,* as specified in FAR part 25, Appendix J, which relate to the Section 25.803 emergency evacuation certification demonstration have been reaffirmed as valid for evacuations conducted through Type-III exits. Secondly, the results suggest that other passenger attributes might be included in such test requirements where the likelihood of significant interactions of such attributes with aircraft equipment and/or configurations could influence specific test results. A third implication is that the design of evacuation studies should benefit from knowledge about the ability of subject experience and/or multiple egress trials to alter the results. For research questions about aircraft configurations, prior experience with aircraft evacuations can reduce the error associated with the *human factors* element always attendant in studies where humans are employed as research subjects. However, other questions, where operational issues are the focus, are generally not amenable to protocols involving such experience, and in either case the results can suffer from poor generalizability without a full evaluation of all the data available. In this regard, analysis of the subject attribute effects conducted herein provided supportive evidence for the conclusions in the McLean, et al. (1995), Type-III exit study, in which dissimilar group egress performance at the 10-inch passageway width had not permitted a decisive answer to the question of what minimum passageway width would produce equivalent safety to that of a 20-inch passageway. There, the minimum passageway width to achieve equivalence was recommended to be 13 inches; that finding was reaffirmed here.

Equally important implications of these results for air carrier operations are: 1) that older passengers can benefit from actual evacuation experience using the Type-III exit and 2) that passenger aircraft operations might utilize such passenger experience to propagate more effective evacuations at Type-III exits during emergencies, especially when trained cabin crew are unavailable to assist. In this regard, the opportunities for older passengers to encounter such evacuation requirements are likely to grow, since the FAA projects that the number of passengers flying on U.S. carriers will double by the year 2012 (ACE Plan, 1994), and The Boeing Commercial Airplane Group has projected that air travel will have grown by the year 2010 to the point that a major accident could easily occur once every week worldwide (see Phillips, 1994). Thus,

opportunities to acquire relevant information and skill about the Type-III exit, as well as other aircraft equipment and procedures, could provide the basis for passengers to be more effective survivors in these instances.

In all, these results show that while many passengers have attributes and limitations that could prevent them from evacuating through a Type-III exit effectively, there are solutions involving both the aircraft and the passengers that could promote the chances of survival in an emergency.

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