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Wayfinding Technology and Its Application to Transport Category Passenger Airplanes

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16. Abstract

Wayfinding, a method to communicate to the public about paths of travel, involves various active and passive modes of communication, such as lights, tactile objects, audio signals, and computer based technology to include virtual environments and augmented reality. A current topic in the field of transport category aircraft is the use of internationally recognized symbols in wayfinding. This is proving to be difficult due to the meanings one culture places on certain symbols and how those differ among cultures. In an era of world-wide travel, this could create a deadly scenario as a passenger is attempting to egress from an aircraft in a dangerous situation, such as a fire, and misinterprets the available wayfinding symbology.

In that vein of research, an eventual goal of mitigating misinterpretation of available wayfinding signals, this overview investigates past and present wayfinding technology used and proposed for use in transport category aircraft and also explores recent advances in wayfinding technology that could be adapted for use in aircraft.

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INTRODUCTION

Wayfinding encompasses all aspects of human travel. As such, it includes the layout of environmental routes that people navigate, including paths through the forest, dedicated roadways between cities, hallways in a building, corridors on a ship, or aisles, passageways, and egress routes on a transport airplane. Wayfinding is enhanced by the signs, symbols, and signals people use to orient themselves (Lynch, 1960). In transportation domains, such aids include roadway markers, informational and directional signs, and internal vehicle signs, placards, and exit locators. Behaviorally, wayfinding describes the actions related to identifying significant indicators regarding getting from one place to another, often requiring the use of complex paths and/or reliance on logic and reasoning. In sum, wayfinding may be seen as a dynamic interaction of humans and technology that, because of the increasing number of travelers and expansion of the number and types of vehicles and potential destinations, demands an ever-growing array of information and presentation technology to yield a safe and successful journey.

Recognition of the need for wayfinding assistance for passengers in transport aircraft emergencies was first established by the U.S. Civil Aeronautics Board, which required emergency exits on transport airplanes to be conspicuously marked and illuminated by a light source independent of the main electrical system (Civil Aeronautics Board, 1953). This basic requirement resulted from the need to guide passengers in emergency events, particularly post–crash events, in which the time allowable to escape the damaged and often burning aircraft was minimal. Since that time, numerous emergency occurrences and advances in technology have prompted the development of improved methods and materials to support wayfinding.

Research on aircraft systems provided to assist emergency evacuations has included studies of design and performance of evacuation assist means, cabin interior layout and lighting, effectiveness of signs and placards, and audio and visual signaling systems, all of which have been considered in terms of wayfinding. Results from many of those studies have been codified in Title 14, Code of Federal Regulations Part 25 (14 CFR 25; Airworthiness Standards: Transport Category Airplanes, 2012), dedicated to assuring the design of safe transport category airplanes, although numerous improvements in wayfinding technology, including those advanced in other domains, have gone without application to transport aviation.

Decisions regarding deployment of such technologies on transport airplanes have typically been based on the ability of any proposed improvement to be integrated into the unique transport aviation operating environment, where the ability to perform appropriately is often dependent on significant tradeoffs in size, weight, energy consumption, and relative effectiveness in the dynamic emergency scenarios typical of aviation. As such, technological advancements shown to be worthy in other environments and applications have often proven unworkable on transport airplanes; concomitantly, innovative thinking about enhanced wayfinding systems and tools for transport airplanes has often been bound by consideration of these operational constraints.

The goal of this review is to evaluate past, present, and proposed adaptations of wayfinding technology in commercial transport aviation, using the taxonomy of human sensory systems and existing applications of wayfinding technology in transport airplane systems as the baseline for analyzing systems and tools derived from developments in modern information technology as prospective new techniques to enhance wayfinding in transport airplanes.

PAST AND PRESENT WAYFINDING TECHNOLOGY UTILIZED ON TRANSPORT CATEGORY AIRCRAFT

Wayfinding involves more than simply placing exit signs next to doors. Lynch (1960) explained that, in the process of wayfinding, people use past memories and immediate sensations to determine their current location and guide them to another location. Understanding what people use to find their way through the physical world and how they process sensory cues from their surroundings has led to the evolution of better wayfinding systems that enhance the prominence of the information markers. Modern safety wayfinding systems may include visual, auditory, and tactile components, which create environments that communicate with travelers, and employ tools (e.g., static and digital signs and maps; radio-frequency identification tags and receivers; vibro-tactile sensors and Braille placards) that enhance the capability of the individual. The extent to which wayfinding is enhanced by these technological enrichments depends on the quality of information transmitted by the technological environment and the receptiveness of the user, especially in situations that demand immediate action.

In aircraft emergencies, passengers rely primarily on their vision to guide them to safety. Generally, vision is the first sense to be affected by the smoke and fumes produced by fire, and according to Deborah Withington (1999), an individual can lose as much as 83% of his or her wayfinding ability when vision is impaired. In such situations normal vision must be augmented by wayfinding technology or vision "substitutions" in order for passengers to navigate the dangerous situation and effect rapid evacuation. The sensory information available to support these activities is available from a variety of sources and wayfinding technology.

Interior Emergency Marking

The aircraft emergency lighting system is the primary means used to support wayfinding in aircraft emergencies. Interior emergency lighting is designed to illuminate escape routes so that people can see well enough to "locate, proceed to, operate, and use cabin emergency exits…to don life jackets, to operate escape means, and to avoid obstacles while moving toward exits" quickly and safely (SAE, 2004).

Title 14 CFR 25.812 (Emergency lighting, 2012) requires that airplanes with more than 10 passenger seats have cabin interior emergency lighting independent of the main lighting system, floor proximity escape path marking, illuminated emergency exit marking and locating signs, and exterior emergency lighting. Emergency power must be supplied to electrically-powered lighting units to provide the required level of illumination for at least 10 minutes after emergency landing, and no more than 25% of the electrically-powered lights can be rendered inoperative by any "…single transverse vertical separation of the fuselage." (14 CFR 25.812(l)(1)). When measured at 40-inch intervals along the centerline of the main passenger aisle(s) and cross aisle(s) at seat arm-rest height, the average illumination provided by the system must be at least 0.05 foot-candle, with a minimum of 0.01 foot-candle at any point within each interval. Additionally, the illumination provided for the passageway leading from the aisle to each floor-level exit must be at least 0.02 foot-candle (measured within 6 inches of the floor).

Some emergency conditions, such as post-crash fires, may introduce smoke into the airplane passenger cabin and obscure the wayfinding aids at the time their prominent visibility is most critical. This effect has been evidenced by many post-crash fatalities that have occurred when smoke has filled the airplane cabin, resulting in passengers' disorientation from loss of visual references for direction and distance to a usable exit, significantly prolonging evacuation times, and resulting in eventual incapacitation. As a consequence, transport airplane regulations require that "means must be provided to assist the occupants in locating the exits in conditions of dense smoke" (14 CFR 25.811(c), Emergency Exit Marking, 2012).

In addition to the general deleterious effects of smoke on passenger wayfinding and survival in airplane crashes, research has confirmed the basis of such effects on wayfinding, especially with regard to ceiling-mounted lights and signs, that are rapidly obscured by dense black smoke entering a transport airplane cabin (e.g., Teal, 1983; Demaree, 1982; Chesterfield, Rasmussen, & Dillon, 1981) and illumination provided by ceiling-mounted lights, which is significantly reduced by even a "thin" layer of smoke near the ceiling. Heavy smoke accumulations block overhead illumination more, masking increases in brightness and further diminishing the effectiveness of lights and signs. Visibility below the smoke layer, however, is hardly impaired, even in "medium" and "dense" smoke conditions, the thermal environment notwithstanding. Demaree (1982) stated that "Under the smoke conditions… it is very difficult for the eye to receive any information from a sign or light located in the ceiling or above the door at the 78-inch level." He recommended that lights located closer to the floor (e.g., on aisle-side armrests of passenger seats) would provide crouched passengers with "…awareness, exit information, and cabin illumination for a substantially longer amount of time than any of the ceiling or bulkhead mounted lights/signs."

Floor Proximity Escape Path Marking

Based on findings from emergency lighting studies, and recommendations resulting from airplane accident investigations conducted by the National Transportation Safety Board (NTSB), a requirement to provide floor proximity escape path marking, in addition to general interior emergency lighting, was established in 1984. The marking system must provide evacuation guidance for passengers when all sources of illumination more than four feet above the floor are obscured by dense smoke, enabling passengers to visually identify the escape path and each exit, relying solely on the markings and visual features that are less than four feet above the cabin floor (14 CFR 25.812 (e), Emergency lighting, 2012). The FAA has accepted a number of combinations of point lighting, flood lighting, strip lighting, markers, signs, reflective materials, and other components that meet the performance objectives of the requirement. In general, "active" floor proximity emergency escape path marking systems require a source of electrical or other power to provide illumination, and "passive" systems provide illumination by emitting light energy collected from the ambient environment, without the need for a power source.

Active Systems

Incandescent lamps and Light Emitting Diodes (LEDs). Typical early floor proximity marking systems installed on transport airplanes were active systems, primarily comprised of incandescent light bulbs placed in tracks on the floor or mounted on seats along the aisle. Fluorescent lights were tested in arm-rest systems but were abandoned because of their poor reliability for starting in certain environmental conditions, extreme cold, for example (Plumly Airborne Products, 1985).

The use of incandescent bulbs in escape path markings has several drawbacks: The bulbs draw more power, require replacement as they burn-out, and suffer from damage caused by vibration and passenger/equipment traffic. LEDs have become an energy-saving alternative to incandescent bulbs. These solid-state devices are much more durable and less likely to fail due to mechanical damage caused by vibration, and have an extended life span, reducing maintenance and replacement costs. LEDs are high-intensity (depending on the level of the current through the semiconductor), narrow-beam point-sources with a minimum of scattered light. High-brightness LEDs, housed in strips of flexible, translucent, fire-resistant silicone rubber or in polycarbonate modules, have been shown to penetrate dense smoke and murky water,

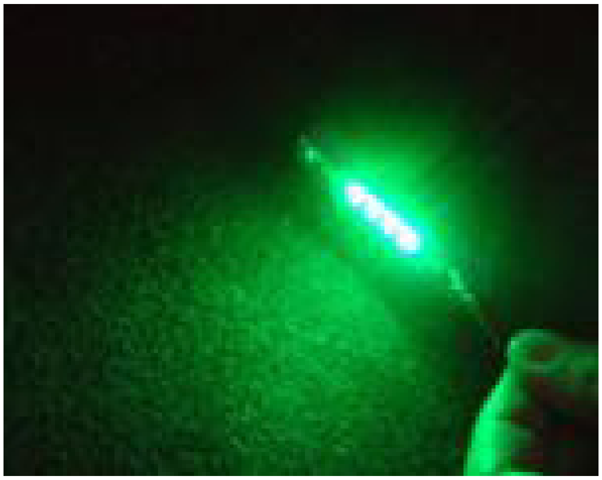

Figure 1. High brightness LED way guidance lighting. Photo courtesy of Oxley Avionics.

providing visual guidance for emergency egress from crashed or ditched aircraft (Oxley Avionics 1998; Figure 1).

Lindsey (1985) suggested that only a point source of light, i.e., the unreflected light from a filament, could penetrate dense smoke, as indirect or reflected light had been shown to provide inadequate illumination for escape path marking. In addition to the highly visible incandescent filaments, SAE ARP 503F (2004) recommends point source LEDs or planar sources of light such as electroluminescent or photoluminescent strips in newer floor path marking systems. All but the photoluminescent strips are active systems, requiring separate, independent power sources, typically emergency batteries.

Directional Indicators. Pulsed and chasing light systems using LEDs, incandescent and other lamps have been developed that give the illusion of movement to indicate the direction to an emergency exit. In 1977, Iwans proposed that programmable, sequentially-firing stroboscopic-type flashing lights located along an airplane aisle would provide “flashing arrows” to direct egress to usable exits only. Johnson, Erickson, and Zamarin (1978) conducted tests on the effectiveness of sequentially flashing lights to direct passengers to exits under simulated smoke conditions, finding that virtually all subjects saw and correctly perceived the direction indicated by the lights when viewed from various angles, under normal and degraded visual conditions. Harrison (1988), developed a flexible carpet underlayment lighting strip apparatus with sequentially-activated incandescent bulbs in light-transmissive plastic housings positioned in holes in the carpet, creating a visually-discernible pathway that appeared along the face of the carpet. Moates (1994) also crafted a system that utilized a flexible strip of LEDs capable of producing a chasing effect with fewer electrical conductors than other systems of the day.

However, potential operational problems with this approach were shown by Johnson et al. (1978), who discovered that most of their subjects would not follow the directional cues, unless instructed to do so, heading instead in the direction of the door by which they had entered the cabin. Furthermore, when faced with an inoperable door, those who were not instructed to locate another exit simply gave up in frustration. With instructions, the sequential flashing lights greatly reduced the number of wrong turns made before turning into the seat row leading to an exit, and decreased the time it took for subjects to ready the exit more than 50%.

Johnson et al. (1978) also identified potential problems that could occur with any automatic system that would direct passengers to an exit: How and when the system would be activated and how the direction of the sequential flashing lights would need to change should an exit and associated escape system become unusable during the evacuation. These shortcomings appear to have made an impression, as SAE (2004) recommended that directional sequencing indicators to specific exits NOT be used, except where a particular exit needs such an indicator. Explanatory information supporting that recommendation is not provided in the technical standard.

Electroluminescence. Escape path marking systems utilizing electroluminescent “lamps” are made up of flat conductors and a layer of dielectric-phosphor mixture that emits a field of light, rather than a point source, when a high-voltage alternating current is applied across the conductors. Current electroluminescent lighting technology provides high visibility in smoke, withstands shock and vibration, and contains no hazardous materials. There are no filaments to break and the material can be cut to length with ordinary scissors (Egress Marking Systems, 2012). Electroluminescent systems have a long life, low power requirements, and can be formed on flexible plastic tapes or strips, making them an attractive option for escape path marking, the need for electrical power notwithstanding.

Active marking systems conclusion. In sum, with regard to active escape path marking systems, battery and wiring failures, burned-out bulbs, and damage caused by vibration, passenger and equipment traffic, and hull breakage during accidents have led to various redundancies to increase their reliability. The evolution of more durable system components and different means of powering emergency lighting systems are at the forefront of new active system technologies; however, advances in passive escape path marking system technologies, particularly photo-reactive materials, have allowed passive systems to dominate in transport airplane applications.

Passive Systems

Photoluminescence. Photoluminescence, the phenomenon of glow-in-the-dark after “charging” with light, relies on inorganic compounds energized by ambient ultraviolet and blue wavelength light energy that is present in nearly all light sources. When the light source is removed, as in a power failure, the photoluminescent materials emit the stored light energy without the need for electricity. These materials are free of radioactivity.

While they have a long history of use, the efficacy of photoluminescent compounds has increased markedly, with current generation compounds having the ability to absorb and emit light at much higher levels and for longer periods than earlier compounds. Photoluminescent exit path markers (and signs) are widely used in buildings, especially in areas where local laws require systems that do not rely on electricity. Such high-performance systems are not affected by water, vibration, fire, heat, or explosion, since they do not contain wires or circuitry. Modern photoluminescent materials have charging times ranging from 5 to 45 minutes, and they provide highly visible exit path marking for up to 16 hours in darkness. Their durability can surpass 20,000 cycles/300 lb. severe-loading airplane galley cart tests. Custom colors, pattern matching, and corporate branding complement cabin décor, reportedly without compromising photoluminescent efficacy. Consequently, photoluminescent technology has become an economical means for meeting the statutory requirements for transport airplane floor proximity escape path marking systems.

In transport airplanes, photoluminescent escape path markers consist of thin, narrow strips of photoluminescent material, encased in a clear housing and affixed to the airplane cabin floor alongside the aisle. They are charged by incident light provided by airplane cabin lighting and natural light that enters the cabin through windows when the shades are open. The elements discharge to provide a luminescent, glowing stripe along the aisle in a darkened cabin (Figure 2). In tests of early generation photoluminescent materials, Aizelwood and Webber (1995) found that people with normal vision had slightly slower egress speeds and greater difficulty detecting obstacles until they were very close to or touching them, as compared with other lighting systems. Similarly, Wright, Cook, and Webber (1999) found that people with poor vision had the slowest egress speeds and reported the greatest difficulty with a photoluminescent system.

In another application of photoluminescent technology, Burbank (2001) introduced photoluminescent fibers woven into carpet or carpet squares. Rather than a lined pathway, the entire aisle was awash with an essentially uniform luminescence across the surface area of the emergency egress path. By omitting the photoluminescent fibers from areas of the carpet, informational indicators such as directional arrows, pictograms or text were used to highlight the pathway (Figure 3). As an alternative design, Burbank selectively wove photoluminescent fibers into the carpet to create large, glowing informational icons, as illustrated by directional arrows 30 and 32 in Figure 4.

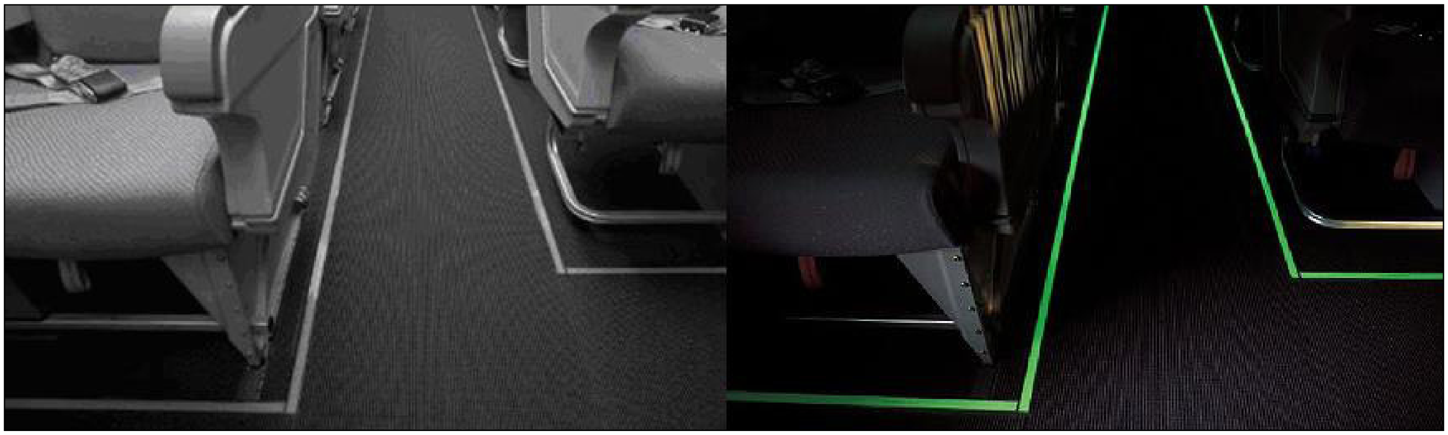

Figure 2. Photoluminescent path marking in lighted and darkened conditions. Courtesy Lufthansa Technik.

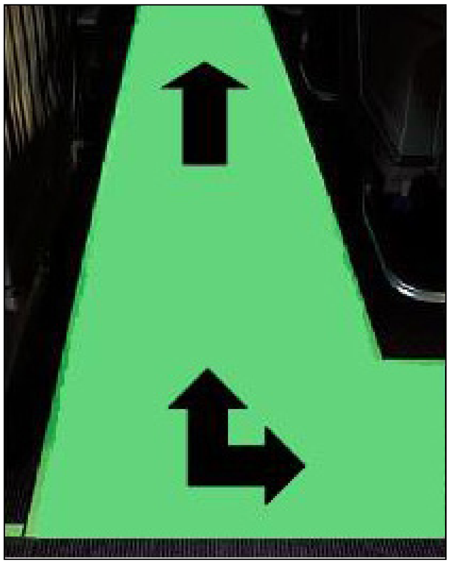

Figure 3. Concept depiction of photoluminescent carpet with non-luminescent directional arrows.

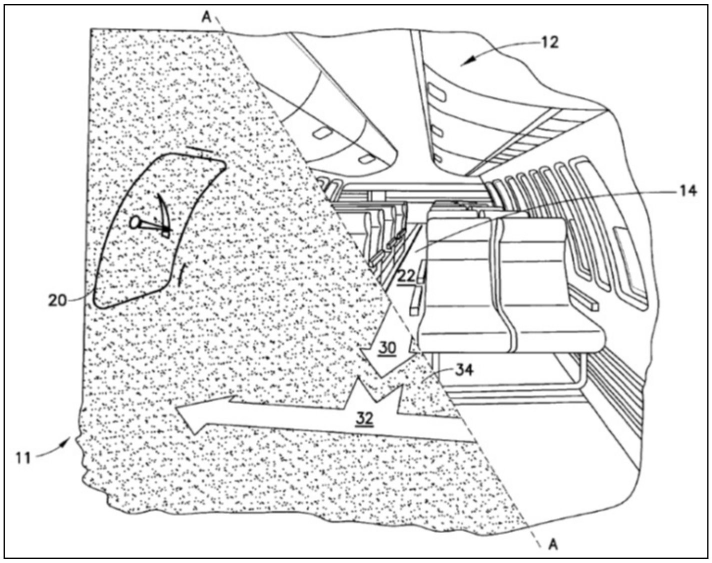

Figure 4. One embodiment of Burbank's design (2001), depicts aircraft emergency escape path marking system (11), employing photoluminescent directional arrows (30, 32) in the non-photoluminescent carpet (22) which serves to guide passengers along the egress path to the exit (20). Reproduced from United States Patent US 6,307,207.

Unfortunately, when the photoluminescent carpet samples were tested immediately following removal of the light source, the intensity and decay rate of the emanating luminous energy was found to be less than that of typical escape path marking strips made with zinc sulfide or particularly, strontium aluminate, as tested by McLean and Chittum (1998) under similar conditions. At 60 minutes total elapsed time, luminance from the carpet sample and zinc sulfide strips had degraded more than that of the strontium aluminate strips, with the carpet sample decline in luminance occurring markedly during the first 10 minutes after removal of the light source, and declining more slowly to about 2x10^{-3} cd/m^{2} thereafter. Importantly, it would be during the first 10 minutes after an emergency that high luminance would be most required.

Advanced photoluminescent pigments and carrier fibers developed since the early studies are claimed to provide higher luminance, sufficient for guiding passengers in an aircraft cabin, although human subject tests as described in FAA AC 25.512-2 have yet to confirm the feasibility of photoluminescent carpet or carpet markings as a floor proximity emergency escape path marking system for airplanes. The in-service effects of passenger traffic, wear, and dirt on carpet markings would also need to be studied.

Tactile systems. Another form of passive wayfinding technology is tactile path marking systems, which are intended to assist passengers who are blind and those with otherwise normal vision that becomes compromised (as in dense smoke), forcing them to rely on their tactile sense. Tactile wayfinding systems are primarily associated with sight-impaired people who rely on Braille for communication. However, studies show that Braille is not universally helpful, as most sight-impaired people do not read Braille, which is a slow process, and Braille-reading ability declines with age, since tactile sensitivity decreases at about 1% per year after age 40 (SAE, 2007; 2008). Undoubtedly, this simple type of passive wayfinding aid would not be very effective for many sight-impaired passengers needing to locate an exit quickly in an emergency.

On airplanes, where the crewmembers are responsible for communicating safety and emergency information to sight-impaired passengers, live or recorded briefings may be supplemented with Braille safety briefing cards and tactile maps to help sight-impaired passengers understand safety and emergency procedures, as well as their location on the airplane in relation to the exits, etc.

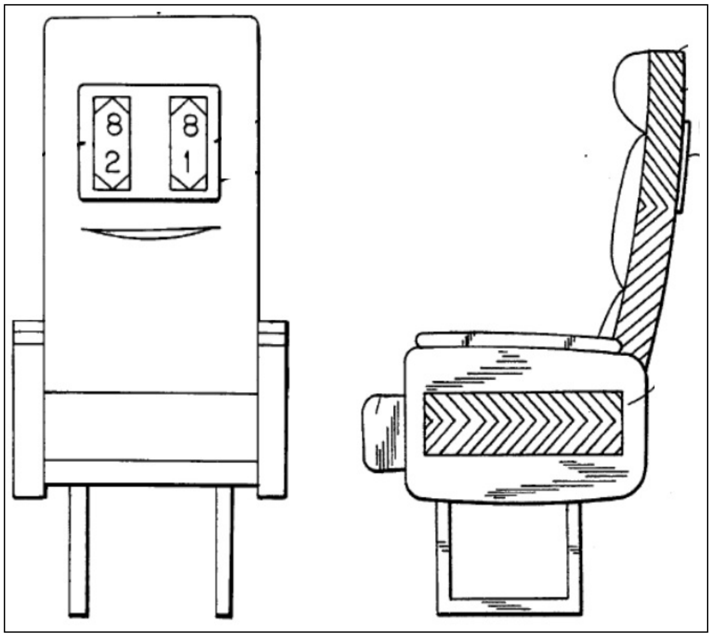

Figure 5. Tactiovisual placards and embroidered upholstery indicate direction and distance to exit (Honigsbaum, 1994).

Tactiovisual (touch-and-sight) wayfinding systems have been developed that can be visually effective when illumination is adequate and tactilely effective in all conditions of visibility (e.g., when smoke, toxic gases and other eye irritants compromise vision). Tactiovisual aids that include Braille and visual components (e.g., lavatory signs, elevator floor numbers and room number signs), serve both sight-impaired and non-impaired people and can be found in most public facilities. Repetitive touch-and-sight-recognizable directional elements (e.g., placards, embroidered or sculpted upholstery) placed on airplane seat armrests, seat backs, and overhead bins in airplane passenger cabins have been suggested to indicate the distance to the nearest exit in either forward or aft direction from that location, and to identify exit row seats and those immediately fore and aft of the exit row (Figure 5; Schriever, 1983; Honigsbaum, 2002). Honigsbaum (1994, 2002) also suggested "vee's" sculpted into carpeting, as well as floor-mounted tactiovisual strips to point out a path to an exit (Figure 6).

As a tactile wayfinding system, a "family" of tactiovisual aids could help passengers during an emergency, especially the sight-impaired. However, the "passive" nature of these aids limits the system as a whole. Such aids would not be able to communicate

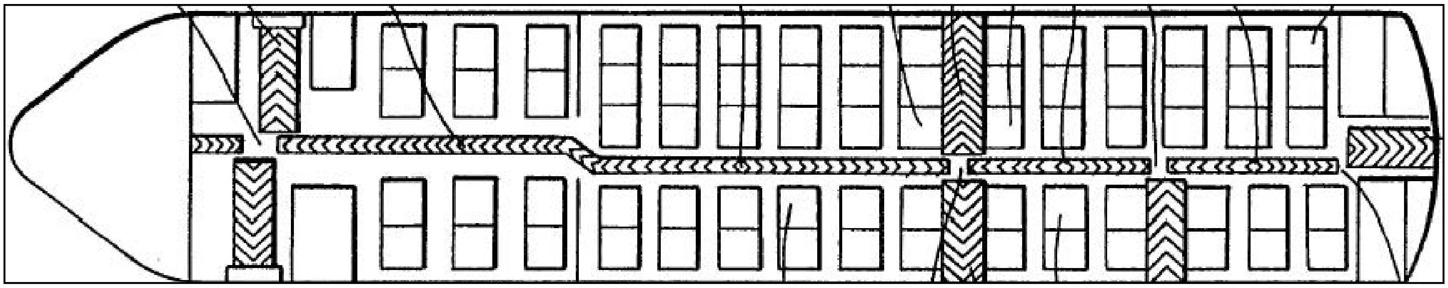

Figure 6. "Vees" sculpted into airplane carpet indicate direction to exits (Honigsbaum, 1994).

Figure 7. A traditional, text-based exit locator sign with directional indicators, which complies with the requirements of 14 CFR 25.812(b)(i).

that an exit is unusable, for instance. Tactile systems could also complement familiar visual systems by serving effectively in all conditions, especially when vision-dependent systems cannot. Again, however, limitations on the use of tactile wayfinding aids, related to the usability of any particular exit during an emergency evacuation, has precluded the widespread implementation of such technology.

Passive marking systems conclusion. Passive escape path marking systems rely primarily on photoluminescent technology, with a small number of transport category airplanes fitted with tactile markers, particularly on the overhead bins directly above the passageways leading to the overwing exits. Photoluminescent systems generally have a single strip placed along one side of the aisle, which changes color at the overwing exit row(s) and which turns toward the exit opening at floor level exits. These systems also include lighted signs below 4 feet at each exit, owing to the need to clearly demarcate the point of egress should the photoluminescent strips be dim from extended discharge.

Figure 8. Common dual language and symbolic exit signs. Latter photo courtesy of Sam Chui.

Interior Emergency Exit Marking and Locating Signs

The exit sign is the primary means of providing information about where to go to get out of a transport airplane. As such, emergency exit signs are required on airplanes by 14 CFR 25.811 and Part 125, Appendix A. The identity and location of each passenger emergency exit sign must be recognizable from a distance equal to the width of the cabin, and its location must be visible to occupants in the main passenger aisle(s). Additionally, means for locating the exits in dense smoke must be provided. With minor exceptions, overhead and bulkhead exit locating signs and exit marking signs next to each exit are required.

Design criteria for the required emergency exit signs are specified in detail in 14 CFR 25.812 and are intended to ensure adequate visibility and readability under normal viewing conditions. Conspicuity, recognizability, and legibility of signs increase with the luminance of signs. For airplanes with 10 or more passenger seats, overhead locator and exit marking signs must be rendered in the English **EXIT** in red, in 1½-inch high letters having a 6-7:1 height to stroke-width ratio, and a 10:1 minimum contrast with the illuminated white background, measuring at least 21 square inches (Figure 7).

In addition to text requirements, internally (electrically) illuminated locator and marking signs required by 14 CFR 25.811 must have a background brightness of at least 25 foot-lamberts and a uniform, high-to-low background contrast no greater than 3:1.

Bulkhead exit locator signs may be self-illuminated (with an initial brightness of at least 400 micro-lamberts), the colors of which may be reversed. This type of sign has often been paired with language translations for airplanes operating in countries other than the USA; additionally, this requirement is being amended in practice by the addition/substitution of symbolic exit signage (e.g., green man running) shown empirically to provide an equivalent level of safety (Figures 8, 9). The intent is to provide language-independent signage identifiable across cultures throughout the international aviation domain.

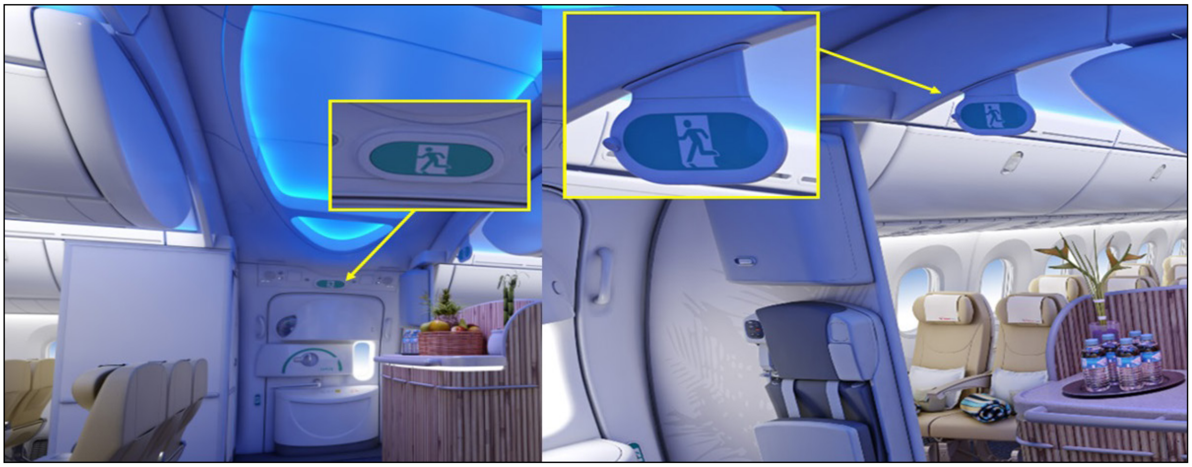

Figure 9. International “Green man running” symbolic exit sign on airplane. Photo courtesy of Thomson Airways.

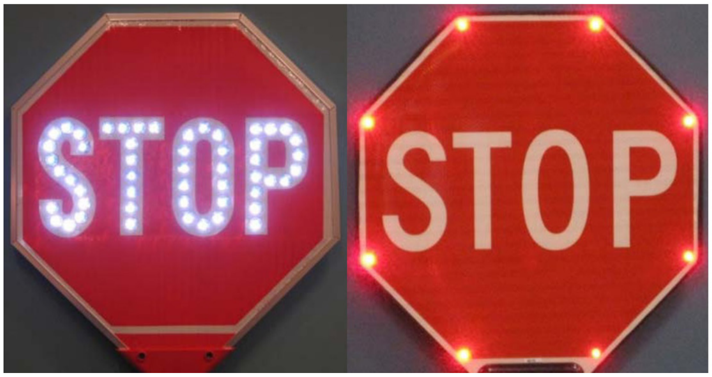

Figure 10. Stop sign enhanced with LEDs in text and on border corners.

Figure 11. The illumination on the wing where an evacuee is likely to make his first step must be at least 0.03 ft-c. On the escape route on the wing, the illumination must be at least than 0.05 ft-c. (From Goodrich Interiors and Lighting Systems, 2003).

The ability of symbolic exit signs to convey the required information has been studied both abroad and within the U.S., the results of such studies indicating that specific design, context, and test participant attributes are important to sign comprehension (Lerner & Collins, 1982; Morley & Cobbett, 1997, McLean & Corbett, 2008). In their research regarding comprehension of airplane passenger safety briefing card graphics/symbols, Corbett, McLean, & Cosper (2008) found that, generally, such graphics are more easily understood by the aviation industry professionals who created them, whereas the naïve passenger, for whom the information is intended, has a lower level of comprehension. These findings highlight potential limitations with using novel representations to convey wayfinding (and other safety) information, i.e., making sure that the intended users are provided information they can understand, which may require that the information is paired with other displays or augmented by training and/or repeated experience.

Regarding the comprehension of the green man running symbolic exit sign, as compared with the comprehension of the EXIT signs required by 14 CFR 25.811/812, McLean and Corbett (2008) found substantial differences in comprehension between the EXIT and the green man running signs, which could be alleviated somewhat when the symbolic signs were presented within the airplane context. Thus, while the case for direct equivalency of wayfinding efficacy was not made, indicating that symbolic exit signs needed to be augmented by additional, compensating elements to improve comprehension, an equivalent level of safety was shown to be achievable via addition of specific passenger briefings, as well as descriptive information printed on safety briefing cards, both of which enhanced familiarity and understanding of the symbolic exit signs.

A current trend in wayfinding has been the addition of flashing LEDs to existing forms of signs to take advantage of the attention-grabbing aspect of flashing lights and the improved economics of using LEDs over other lighting technologies (Bullough, 2011; Bullough, & Skinner, 2009). Research examining the effectiveness of adding flashing LEDs, in a variety of configurations, to traffic control signs and markers has shown that they increase sign conspicuity, especially at night, and result in reduced cases of driver non-compliance with signs by up to half. The most effective configurations have the flashing LEDs on the border of the sign, either on the corners or around the entire border (Figure 10; Arnold & Lantz, 2007; Finley, Ullman, Trout, & Park, 2012; Gates, Hawkins, Chrysler, Carlson, Holick, & Spiegelman, 2003; Huff, 2011). Research evaluating the addition of LED lights to crossing guard and construction worker stop/slow paddles showed similar advantages for flashing border, LED-enhanced signs (Huff, 2011). Consistent throughout the research was the finding that sign effectiveness is reduced if the text on a sign is enhanced with LEDs, which makes the signs harder to see and comprehend than a border configuration (Figure 10). Currently, aircraft escape path marking systems do not incorporate flashing lights on the marking or locator signs.

Exterior Emergency Lighting

Title 14 CFR 25.812 (g)-(h) requires aircraft exterior emergency lighting at each emergency exit (with and without descent assist means), along the escape routes (Figure 11), on any descent assist means required for exits more than 6 feet from the ground (Figure 12; 14 CFR 25.810), and on the ground surface where an evacuee would make first contact

Figure 12. An example of escape slide lighting systems. Left: Incandescent lighting, Center: LED lighting, Right: Ground-illuminating LED lights at end of slide (BaseWest, http://basewest.com/slidelight products/escape-slide-lighting).

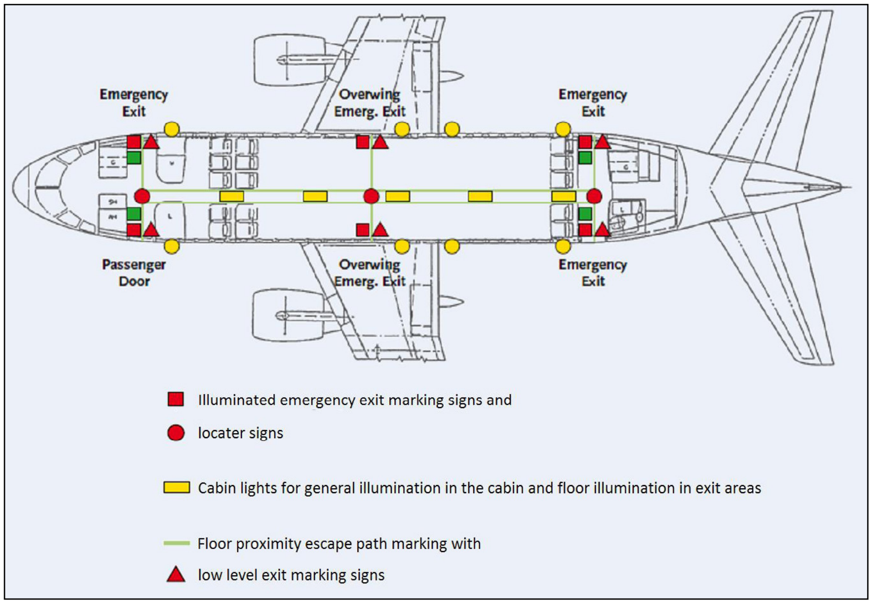

Figure 13. An emergency lighting system for transport airplanes meeting requirements of 14 CFR 25.812 (From Goodrich Interiors and Lighting Systems, 2003).

Provisions similar to those for interior emergency lighting must also be made for continuity of emergency power in the event of fuselage damage. SAE (2004) recommends placing exterior lights such that illumination is not obstructed by deplaning evacuees, descent assist means, and doors/hatches, as well as locating the lights high enough to prevent submersion when the airplane is in the anticipated floating attitude after an emergency landing on water. (An example of an emergency lighting system for transport category airplanes is shown in Figure 13.)

LED technology has provided significant improvement in exterior emergency lighting, much like it has to interior emergency lighting (Figure 12). LEDs withstand harsh conditions and provide high-intensity light. Combined with advancements in wiring and electronics technology, exterior emergency lighting systems have become compact, and are crush- and chemical-resistant.

PROPOSED WAYFINDING TECHNOLOGY FOR TRANSPORT CATEGORY AIRPLANE SYSTEMS

Application of wayfinding technology on passenger-carrying airplanes is rooted in 14 CFR 25, which prescribes the design and performance of lighting, signage, and floor proximity escape path marking systems, in particular. Technology outside the bounds of these requirements (e.g., green man running symbolic exit signs) has been allowed by way of an equivalent level of safety (ELOS) finding with previously approved system elements. As such, unique or novel technological innovations have often gone wanting when it comes to certification for use aboard transport category airplanes, resulting in a state-of-the-art that has only changed minimally over the last few decades. The advent of escape path marking systems in the 1980s was the last major advancement, with subsequent changes from incandescent bulbs to LEDs and red EXIT signs to the green man running symbolic signs representing minor evolutions in onboard wayfinding aids for passengers. As noted earlier, the special challenges produced in the transport airplane emergency operating environment limit many innovations, such as directional indicators to exits; the typical response to these constraints has been through the use of flight attendants trained to understand and manage emergency operations. Recently, however, a new class of wayfinding technology has emerged that offers passengers the ability to become better trained, themselves; the various implementations of this technology offer a range of approaches now familiar to anyone with a computer, smart phone, or interactive electronic gaming device.

Light Amplification by Stimulated Emission of Radiation (LASER) Technology

The use of laser devices has grown rapidly in recent years and "laser guidance" has taken on new meaning since its sci-fi and top-secret weapons origin. Now, plasma laser walls across street intersections can replace traffic lights, increase pedestrian safety, and improve driver awareness (Garder, Monterde-i-Bort, Johansson, Leden, Basbas, and Schirokoff, 2012; Figure 14). Lighted exit signs can be equipped with LED lasers that are visible through fog and smoke and fan out over a room to provide guidance to a usable exit (Belanger, 2009). Lasers can produce a ceiling-to-floor corridor of sequencing laser light columns, or "projected" arrow indicators, graphics, or alpha-numeric indicators to show the path and direction to an exit (Lehman, Gechtman, Fuller, and Hreha, 2000).

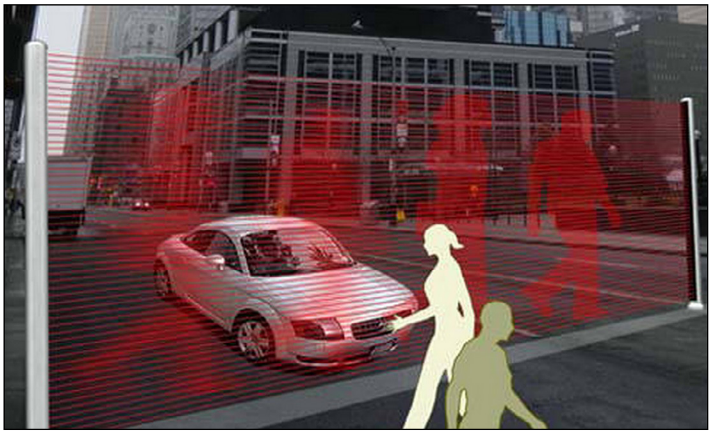

Figure 14. Laser "virtual wall" across pedestrian crossing zone. (Garder et al., 2012)

The visible range of lasers depends on wavelength (color), output power, and environmental factors. For typical laser "pointers," the most common are red or red-orange, with wavelengths ranging from 630 to 680 nanometers (nm). Green lasers emit a 532-nm beam of light, which is near the eye's peak sensitivity, resulting in exceptional brilliance and visibility. Green laser diodes are considerably more expensive than red diodes and require a high electrical current, which depletes battery power rapidly (Nakagawara & Montgomery, 2001). Figure 15 shows different colored lasers in a simulated smoke-filled airplane cabin with cabin lights on and off. Airborne particulates make laser beams more visible. Consequently, as smoke becomes thicker, the laser light signals become brighter and more visible, unlike other types of lighting.

Unfortunately, the use of laser beams for wayfinding comes with some potential hazards that may not have been considered by developers of laser guidance systems. Because of the refractive nature of the human cornea and lens, the light energy that lasers can deliver may be more damaging to the retina than staring at the sun. According to Nakagawara and Montgomery (2001), the risk of injury occurs when energy level and duration of exposure increase absorption of laser energy in the retinal tissue. Even with low-power laser outputs (< 5 milliwatts), injury can occur from exposure for only several seconds to a few minutes at close range (10 feet or less). Momentary exposure may not cause permanent physical damage, but discomfort, temporary visual impairment, spatial disorientation, and loss of situational awareness can occur. Although temporary, these effects "can be hazardous if the exposed person is engaged in a vision-critical activity…."

Auditory Systems

As noted earlier, vision is the first sense to be affected by the smoke and fumes produced by fire (Withington, 1999). Working from the premise that some of the effects of visual impairment could be mitigated by the inclusion of auditory signals to draw passengers towards functioning exits, Withington's (2004) research has demonstrated that the use of directional sound can reduce evacuation times by a third or more.

Auditory wayfinding research, using directional sound technology, is generally focused on the ability of the human binaural auditory system to localize sounds (i.e., identify the spatial location of a sound source). It further assesses the types of sounds and signals that are the most identifiable and communicable, vis-à-vis the appropriate information. Localizing a sound requires an enormous amount of neural processing by the human brain, and the sounds must contain a wide spectrum of frequencies, i.e., broadband noise, so as to provide the maximum number of "cues" available to process and be directionally identifiable (O'Connor, 2005; Wightman and Kistler, 1993; Merat, Groeger and Withington, 1999). Complex tone signals comprised of many components with varying frequency and amplitude have

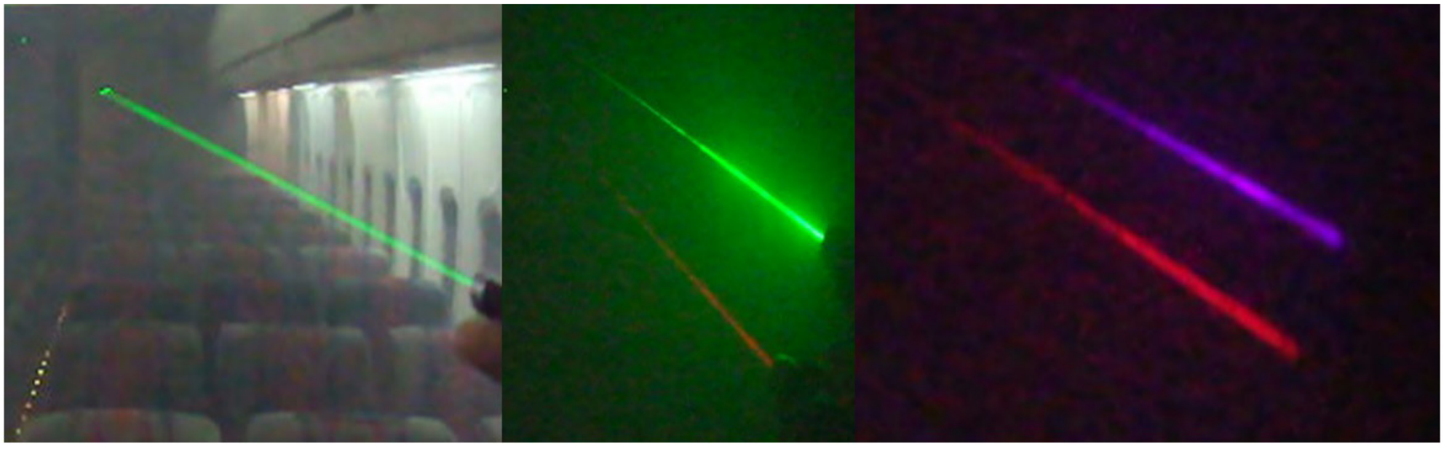

Figure 15. Handheld laser pointers in smoke.

been shown to approximate the localizability of broadband sound (Lower, Kay, Thomas, and Muir, 2004).

Early studies of localizable signals suggested that non-speech sounds might be more resistant to being masked by "babbling voices" than speech sounds (Tobias and Curtis, 1959; Mosko and House, 1971). However, Tobias and Kidd (1979) found human voices, calling out "Exit here," "This way," "This way out," during simulated emergency evacuations, to be more effective than non-speech signals in directing passengers, whose vision was obscured by smoke goggles, toward the nearest exit in a darkened aircraft cabin. In a series of pilot studies that included speech directions to exits, or a choice of exits, in smoke-filled rooms and complex mazes, Withington (1999) consistently found that the directional sound units improved evacuation time, especially when the participants were given information about the sounds and the layout of the test space. In a study using signals that included two high-pitched "dinner-bell" tones followed by the spoken message, "exit here," to indicate exit locations in a road tunnel filled with smoke, Boer and Wijngaarden (2004) found that 87% of the participants walked from the bus that was stopped in the roadway, straight to the nearest tunnel exit, with a hand outstretched to avoid collision with obstacles.

Withington (2001) investigated the use of directional sound units to aid aircraft evacuations from a smoke-filled, twin-aisle aircraft cabin. In a simulated flight, the "passengers" were given a standard preflight briefing, with an additional announcement about, and demonstration of, the directional sound devices. Exit usage improved as the sounds directed passengers away from unusable exit to usable exits, which the cabin crew, acting alone, were unable to achieve. All of the cabin crew reported that the sound had not hindered their actions to evacuate the passengers, and 90% of the passengers reported that the sounds helped them find a usable exit.

Researchers have found that the area of the human brain that responds to spatial sensory information and initiates the response to sensory stimuli contains neurons that respond to both sound and light. When sound and light signals are presented together, response is greater than the sum of responses to light and sound when presented individually, sometimes more than 500 times greater (Withington, 2004). Consequently, a combination of both visual and auditory components should comprise an effective wayfinding system. Unfortunately, the inability of technologists to develop a transport airplane wayfinding system that can be "tuned" to recognize an emergency exit that becomes unusable during an emergency evacuation, because of developing fire or another emergent hazard, has precluded the application of auditory signaling technology in transport airplane wayfinding systems.

Electronic Information Technology

Virtual Environments

Scientists began investigating the use of virtual environments (VE; i.e., computer-simulated environments that simulate physical presence in real or imaginary worlds) to conduct research in the early 1990s, due, in part, to the reduced cost and ease of replicability, as compared with running experiments in the physical world (Satalich, 1995). Researchers have investigated the difficulties inherent in navigating in a virtual, abstract environment, without the use of various senses (Charitos, 1997, Chen & Stanney, 1999) and the effectiveness of different navigational aids within the VE.

Wu, Zhang, and Zhang (2009) evaluated human-system collaboration, animation guide, and view-in-view map navigation aids in VE. In the human-system collaboration, participants were given cardinal directions along the route by the system. The animation guide showed a floating view of the route, starting at the same point as the location of the participant, rising above the environment and then descending towards the end point of the participant's route. The view-in-view map gave the participant a small, persistent virtual map of the environment in the corner of the computer screen. The results showed that all three aids helped participants find targets quicker and easier, though both the animation guide and view-in-view map produced better results than the human-system collaboration. The view-in-view map produced shorter route navigation times and reduced cognitive load better than the other navigation aids. Prior research using aids similar to view-in-view maps showed that subjects did better with a two-dimensional representation, as compared to a three-dimensional mini-map (Chittaro & Venkataraman, 2006).

In their study that examined working memory systems relevant for wayfinding, route-learning, and potential interference effects on performance, Meilinger, Knauff, and Bülthoff (2008) had participants learn two routes in VE while they were confronted by a visual, spatial, or verbal secondary task (no secondary task in the control group). The participants then had to retrace the routes they had been given (without the secondary task). The researchers found that the verbal and spatial secondary tasks interfered more with learning route information, leading to worse performance during the wayfinding phase. Participants in the verbal task group also got lost more than those in the other groups. These findings replicate more general effects on selective attention found in real-world situations, and their importance for applications in wayfinding becomes clear when a larger purpose of VE research is considered: simulation and modeling.

Simulation studies in VE have been used to determine, in a cost-effective manner, the efficacy of other wayfinding aids, such as signs (Tang, Wu, & Lin, 2009). Other simulations have looked at reproducing safe evacuation behavior in fires. Such simulations give the ability to easily change aspects of the wayfinding aids to test the effectiveness of competing renditions (Smith & Trenholme, 2009).

Modeling studies conducted in VE began with the development of a multi-agent-based model, in which the "agents" represent individuals whose behaviors are based on probability models and sets of heuristics, or rules (MASSEgress, Pan, Han, Dauber, & Law, 2007; airEXODUS, Galea, Filippidis, Wang, Lawrence, & Ewer, 2010). For example, Galea et al. (2010) conducted experimental evacuation trials with humans, using a cabin mock-up of the rear corner section of a blended-wing-body

Figure 16. Example of digital graphics overlay application showing an integrated world of digital and physical information for navigation.

Figure 17. Example of an X ray AR navigation tool showing the destination through a building blocking physical line of sight.

aircraft, and full-scale model simulations using airEXODUS. The researchers reported that the experimental trials supported the overall findings of the modeling simulations. Researchers at Rutgers University have developed an analogous agent-based aircraft evacuation model (EVA) using genetic, as well as hill-climbing, algorithms (Gea, 2004). The application of the findings from these simulated and modeling efforts toward airplane interior design and emergency procedures offers the ability to improve emergency evacuation performance from both structural and operational perspectives.

Augmented Reality

The concept of Augmented Reality (AR) has existed since the 1990s, with its definition coming from Azuma's (1997) review of the state of the art at that time. AR combines the real and virtual worlds, interacts with and provides feedback to the user in real time, and is registered in three dimensions (Figure 16). Applications of state-of-the-art AR technologies include training, education, medicine, entertainment, and navigation (Goldiez & Liarokapis, 2008). Heads-up displays (HUD), helmet-mounted sights (HMS), and head or helmet-mounted displays (HMD) and Battlefield Augmented Reality System (BARS) used for targeting and navigation by the military are AR systems that have been shown to improve navigation over non-augmented systems (Goldiez, 2004; Goldiez, Ahmad, & Hancock, 2007).

Portable displays or "smart" devices such as smart-phones or tablet computers also have AR applications. Generally, AR navigation applications on handheld devices follow two paradigms; X ray AR (see-through) navigation and mixed-reality navigation (Figure 17). X ray AR navigation refers to a technique similar to the HUD/HMD design of constantly seeing the real world with a digital graphics overlay showing an integrated world of digital and physical information, in some cases allowing users to "see-through" buildings in the real world to get a better sense of their destination. Research conducted with X ray AR navigation applications showed that users spent more time during the navigation task looking through the AR mobile application while walking, thus getting a view of both the real world and digital information through the camera of the phone, than other navigation techniques, such as GPS or world in miniature map navigation applications (Dey, Jarvis, Sandor, Wibowo, & Mattila, 2011). According to the authors, this is beneficial for the users of the technology in that it reduces cognitive load by reducing the number of context switches from real world to phone, which results, over the long term, in less mental fatigue while navigating and fewer errors in navigation.

Mixed reality navigation applications utilize both AR and virtual reality (VR) techniques to assist users in wayfinding. Mulloni, Seichter, and Schmalstieg (2011a), using both X ray AR navigation and world-in-miniature navigation maps, found that users prefer the X ray AR mode while walking, and the world-in-miniature aspect at major decision points and intersections.

Mixed reality systems in areas with sparse information availability, due to either a lack of wireless/cellular information services of a lack of navigation information in an indoor setting, use strategically placed information nodes, such as digitally coded information posters or data transmitting nodes, that users examine with their AR device to get information about their surroundings and how to get to the next information point or their destination (Mulloni, Seichter, & Schmalstieg, 2011; Mulloni, Seichter, & Schmalstieg, 2012). Between the information points, users rely on a combination of pedestrian locomotion and direction (walk forward X steps) in a world-in-miniature map to navigate. This system could be adapted for use on an aircraft by including imbedded information delivery systems, such as the digitally coded physical map, for passengers to scan into their digital devices that would then provide information to navigate to an emergency exit in emergency situations when other visual wayfinding systems are obscured. Another potential application of AR for aircraft passenger navigation during an emergency is projector-based and an adaptation of a system developed by Chung, Kim, & Schmandt (2011) for use with mobile devices.

Wayfinding information is received from the surrounding environment through a small hand-held camera. This information is then transmitted through a small hand-held projector that displays necessary navigational information. For example, the projector can display an arrow indicating the direction the user needs to walk to reach a specific office within a building.

Both VE and AR approaches require large investments in infrastructure and supporting equipment, making adoption of these technologies on transport airplanes unlikely. Importantly, however, developments in these areas have spawned related improvements in interactive information processing and representational systems, including incorporation of motivational techniques by which to enhance user learning and performance.

Persuasive Technology

Advances in technology have produced excellent tools to help people find their way to safety during emergencies and in the worst of environmental conditions. Typical wayfinding systems produce prominent sensory cues that can enhance the physical capability of the individual. However, behavior and survival psychologists have found that people commonly ignore the possibility that they might face a particular threat and will react with disbelief and denial, even when the threat is imminent (Williams, 1964; Leach, 1994). Such a person is not likely to prepare for an emergency, as planning and preparation are inconvenient and physically/mentally demanding, especially for an event that "will never happen!" Even after many years of attempts by aviation safety professionals to educate passengers about safety, the majority of passengers still fail to attend to minimal safety information: They ignore preflight safety briefings, and they do not read the safety briefing cards (NTSB, 2000; Corbett & McLean, 2004; Muir & Thomas, 2004; Chang & Liao, 2009).

Research has shown that passenger knowledge is a key factor in determining how people will respond in an emergency. The airplane passenger who has paid attention to the safety information available, who is familiar with the configuration of the airplane cabin, and who has developed a plan for what he or she would do to get out of the airplane in a hurry, would be better able to handle an emergency situation and would be better prepared to utilize the wayfinding system that has been provided for safe and rapid evacuation. The two major knowledge-based tools routinely provided to passengers are the preflight safety briefings and safety briefing cards, both of which have been shown to suffer from serious limitations and effectiveness. Even those passengers who report that they pay attention to the briefings and cards have little personal knowledge and understanding of the safety and survival information they have been given (Corbett, McLean, & Cosper, 2008; Corbett & McLean, 2004).

Research further suggests that well-constructed passenger education programs and materials that include substantially more appealing and comprehensible safety and survival information need to be developed to help increase the probability of passenger attention and, ultimately, passenger survival during emergencies. Recommendations for state-of-the-art methods have included interactive CD-ROMs (Cosper & McLean, 2004) and hands-on safety education exhibits at airports (Chang & Yang, 2011). Yet, a major problem remains: overcoming the apathy and denial that such information is necessary in the first place.

Persuasive Technology (PT) is a relatively new endeavor and is among the more innovative tools for promoting safety and disaster preparedness, as well as environmental conservation, occupational productivity, preventative health care, fitness, disease management, personal finance, community involvement, and personal improvement (Fogg, 2003). PT works by providing tailored information, triggering decision making, and simplifying or guiding people through a process that increases self-efficacy (Tombari, Fitzpatrick, & Childress, 1985). Recent investigations using PT have looked at how virtual simulations of risk experiences can be used to change peoples' attitudes and behaviors with respect to personal safety (Chittaro & Zangrando, 2010; Meijnders, Midden, & McCalley, 2006; Zaalbert & Midden, 2010). Through interactive computer simulations, immersive virtual environments, and compelling serious games (SGs) that often use principles of operant conditioning (without coercion or deceit), researchers have shown that people can be "persuaded" to change their attitudes and modify their behavior by immediately showing them the effects of their choices (Chittaro, 2012; Khaled, Barr, Noble, Fischer, & Biddle, 2007; Chittaro & Zangrando, 2010). The goals of a persuasive tool for aviation safety include developing personal safety involvement and skills among passengers, and increasing their knowledge and self-efficacy through a virtual life experience.

Serious Games

Serious games are simulations of real-world events or scenarios designed specifically to inform and train individuals (i.e., for problem solving), rather than provide pure entertainment. They are often used by industries like defense, scientific exploration, emergency management, and city planning (Ribeiro, Almeida, Rossetti, Coelho, & Coelho, 2012). As early as 1970, Clark Abt defined serious games in reference to board and card games, "We are concerned with serious games in the sense that these games have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement." More recently, Mike Zyda (2005) provided an update to the term: "a mental contest, played with a computer in accordance with specific rules that uses entertainment to further government or corporate training, education, health, public policy, and strategic objectives." By leveraging basic intrinsic motivators, i.e., challenge, curiosity, fantasy, control, competition, cooperation and recognition, SGs can be engaging, attractive, and entertaining, so people will want to use them for long periods of time, thus increasing exposure to particular information and making its retention more likely.

The creation and use of serious games for training and study of evacuation behavior has focused primarily on fire drill behavior and building evacuations (Ribeiro, Almeida, Rossetti, Coelho, & Coelho, 2012; Smith & Trenholme, 2009). In a study in which players who were allowed to play through a game only once, Ribeiro et al. found that players did learn evacuation procedures from the activity, but concluded that although the game environment has proven to be an invaluable tool for training, it does not replace the need for "live" drills to train people in emergency situations.

Serious games have also been effective in educating airplane passengers about egress routes and dangers associated with evacuation (Chittaro, 2012). While some airlines are attempting to attract passengers' attention to preflight safety briefing videos and briefing cards by making them humorous, fun, or employing celebrities as speakers, they are limited by their non-interactive nature. SGs give the passenger a detailed and dynamic visualization of the specific airplane cabin, its safety equipment, the procedures to follow, and the ability to see how the cabin changes in different emergency scenarios (e.g., presence of fire and smoke) with changes in their own behavior, as well as the resulting challenges and advantages such changes present. The gaming passenger can look over the entire cabin from any viewpoint, including his or her precise seat and/or other viewpoint resulting from movement within the cabin, to maximize information intake and comprehension. The passenger's virtual character moves around, exploring the emergency evacuation scenarios in an experiential way, performing actions within a virtual crowd of passengers and cabin crew. The SG assesses whether the passenger has comprehended the safety instructions and provides personalized feedback regarding elimination of errors in case of a real emergency (Chittaro, 2012). The similarity that can be achieved between the SG simulation and real life, combined with the cost-effective reusability of the game, allows a user to gain knowledge and survival skills in a safe and effective manner.

SUMMARY

Wayfinding technology has a long history. Today's state of the art is the product of extensive research over many decades, with devices that can be utilized in almost any setting. This review has examined wayfinding technologies that are presently used or could be adapted for use on commercial transport category airplanes to enhance passenger wayfinding during emergency evacuations. However, unless there is a significant financial incentive, a decrease in the amount of energy required to operate them, or a weight reduction relative to current systems, innovative wayfinding aids are often left "on the drawing board." This occurs, in part, due to the low occurrence of airplane emergencies resulting in the need for evacuation, which means such systems are infrequently required, with the implementation of newer technology appearing to have a negative cost/benefit ratio.

In contrast, passenger safety research and accident investigations have shown that getting passengers involved in the safety "equation" can be critical to their survival, and yet, that is one of the biggest hurdles to overcome, as passengers fail to engage the safety information provided to enhance survivability. The most recent advancements in pursuit of enhanced wayfinding have resulted from investigations using persuasive technology, via electronic audiovisual media (i.e., virtual environments, augmented reality, and serious games), which until recently have not been applied directly to transport aviation safety. Recent research, however, has shown that these tools present a most promising means to overcome the challenges of passenger apathy and to promote passenger safety awareness, knowledge, and survival skills.

Future research in the area of serious games should include further design and evaluation of novel, interactive techniques to enhance persuasive interaction, test modes of providing interactive safety information (e.g., humorous, neutral, scary), and identify those techniques which are most effective or for which population segments each technique could be made more effective. Investigating ways to further tailor evacuation scenarios and emergency procedures could support the high-level definition and creation of interactive 3D virtual environments programmable by safety experts who may have minimal computer programming experience.

Finally, modern information technology allows SG to be available on a variety of electronic platforms, including airline and other industry/government websites, in-flight entertainment systems, and passengers' own portable devices, such as tablets and smart phones. The ability of information technology developers to use off-the-shelf technology to create and modify SG scenarios to represent different types of aircraft and wayfinding aids in emergency scenarios points toward SG as an important advancement in aircraft safety and wayfinding. SG technology could include on-line flight check-in capabilities, turning a passenger's mobile device into a personal safety tool, tailored with the specific airplane type and seat assignment, for use at home or at the airport, thereby increasing exposure time to potentially life-saving information. Thus, while not a wayfinding aid in the traditional sense, SG provides a potential leap forward in gaining passengers' attention and enhancing their survivability in an aircraft emergency.

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