

**CONTEMPORARY PRACTICES IN STAIRWAY DESIGN:
BEHAVIOR OF STAIR USERS IN PUBLIC BUILDINGS**

by

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Table of Contents

Acknowledgements	iii
List of Tables	vii
List of Figures.....	viii
Abstract.....	ix
 Chapter 1	 2
1. Introduction.....	2
1.1. Research Aims	2
1.2. Stair Safety Background	2
1.3. Stairway Design Assessments.....	5
1.4. Research Design.....	6
1.5. Chapter Summaries	7
Endnotes to Chapter 1	9
 Chapter 2	 10
2. Stairway Design Practices	10
2.1. Abstract.....	10
2.2. Introduction.....	10
2.3. Methods	12
2.3.1. Journal Sample.....	12
2.3.2. Checklist Development	13
2.3.3. Procedure	14
2.4. Results.....	14
2.4.1. Stairway Design in the Professional Media	14
2.4.2. Stairway Hazards	18
2.4.2.1. Railing.....	18
2.4.2.1.1. Missing or inadequate handrails	18
2.4.2.1.2. Handrails were not fully extended	19
2.4.2.1.3. Handrails were too wide or too thin.....	20
2.4.2.1.4. Missing or inadequate balustrades	21
2.4.2.2. Visibility	22
2.4.2.2.1. Low visual contrast on tread edges	22
2.4.2.2.2. Open risers	23
2.4.2.2.3. Poor lighting	24
2.4.2.3. Step geometry	25
2.4.2.3.1. High or low riser to tread ratio.....	25
2.4.2.3.2. Irregular riser height or tread depth	26
2.4.2.3.3. Narrow stairway width.....	28
2.4.2.3.4. Short tread depth.....	29
2.4.2.4. Other hazards	30
2.4.2.4.1. Excessive length of stairway run	30
2.5. Discussion.....	32
2.5.1. Research Questions	32
2.5.2. Stair Safety Education.....	34
2.5.3. Limitations and Future Work.....	36
2.6. Summary and Conclusion.....	37
Endnotes to Chapter 2	38

Chapter 3	40
3. The Effects of Glass Stair Treads on Stair Users in an Apple Retail Store	40
3.1. Abstract	40
3.2. Introduction	41
3.3. Methods	43
3.3.1. Hypotheses	43
3.3.2. Exploratory Study	44
3.3.2.1. Protocol	44
3.3.2.2. Procedure	44
3.3.3. Comparison Study	45
3.3.3.1. Procedure	45
3.3.3.1.1. Comparison Site Selection	46
3.3.3.1.2. Checklist Development	47
3.3.3.1.3. Collection and recording of data	49
3.4. Results	49
3.4.1. Exploratory Study	49
3.4.2. Comparison Study	50
3.5. Discussion	53
3.5.1. Visibility of Glass Stair Treads	53
3.5.2. Visual Distractions in the Apple Retail Store	54
3.5.3. The Direction of Stair Curvature	54
3.5.4. Gait Characteristics and Strategies in the Apple Retail Store	55
3.5.5. The Use of Glass As a Flooring Material	57
3.5.6. Limitations and Future Work	59
3.6. Conclusion	60
Endnotes to Chapter 3	62
Chapter 4	64
4. The Effects of Interactive Sound on Stair User Behavior and Safety	64
4.1. Abstract	64
4.2. Introduction	65
4.3. Methods	68
4.3.1. Hypotheses	68
4.3.2. Protocol	68
4.3.3. Feasibility Test	68
4.3.4. Site Selection	69
4.3.5. Checklist Development	70
4.3.6. Collection and recording of data	72
4.4. Results	73
4.5. Discussion	76
4.5.1. Interactivity in Stair Performance	76
4.5.2. The Use of Interactive Stairways as Technology and Art Exhibits	77
4.5.3. Limitations and Future Work	80
4.6. Conclusion	81
Endnotes to Chapter 4	82
Chapter 5	84
5. Conclusion	84
5.1. Research Summary	84
5.2. Chapter Summaries and Results	84

5.3. Future Work	86
5.4. Conclusion	87
Bibliography	88

List of Tables

Table 1. Summary of stairway evaluations by year ($N = 855$ stairways).	15
Table 2. Stairway hazard categories ($N = 1,207$ stairway hazards).	16
Table 3. Unsafe stairways by number of hazards ($N = 645$ unsafe stairways).	17
Table 4. Profile of stairway portions observed in an Apple Retail Store and a shopping mall.	47
Table 5. Results of the exploratory study with a 6 hour sample of stair use.....	50
Table 6. Cross-site comparison of the incidence of hesitation, misstep, and loss of balance during descent on the glass stairway and the conventional stairway.	51
Table 7. Profile of the stairways in the museum buildings and the university building. ...	70
Table 8. Cross-site comparison of the incidence of hesitation, misstep, and loss of balance during descent on the interactive stairways and the conventional stairway.....	73

List of Figures

Figure 1. Stairway design hazard checklist.....	13
Figure 2. Stairway hazards by setting ($N = 855$ stairways).	15
Figure 3. Most common stairway hazards in <i>Architectural Record</i> (2000-2010).	17
Figure 4. A stairway with a thin truncated handrail, inadequate balustrades, and low visual contrast on the tread edges (Photographer: Toshiyuki Yano).	20
Figure 5. Visual distractions in an open riser stairway (Photographer: Kouji Okamoto / Techni Staff).	24
Figure 6. A narrow stairway with variation in tread size (Photographer: Michael Moran Photography).....	28
Figure 7. A stairway with an excessive stair run length (Photographer: Elizabeth Felicella).	31
Figure 8. A stairway with glass treads (Photographer: Roy Wright Photography, Inc.). .	34
Figure 9. Selected stairway sites for cross-site comparison of stair use: glass stairway at an Apple Retail Store (left) and a conventional stairway at a shopping mall (right).	46
Figure 10. Observation checklist.	48
Figure 11. Cross-site comparison of key behaviors.	52
Figure 12. Interactive stairways at a Children's Museum (left) and a Science Museum (right).	69
Figure 13. Observation Checklist	71
Figure 14. Cross-site comparison of key behaviors.	75
Figure 15. A stairway with LED color displays on stair risers (Source: YouTube user heinv, retrieved from youtube.com/watch?v=uGEGyaxV9SU)	79
Figure 16. A stairway with confusing tread pattern at the Albright-Knox Art Gallery (Source: M. Frederick).....	79

Abstract

Safety is a top priority for building users and should be a primary goal for architects when designing public buildings. Stairway falls continue to be one of the main causes of injuries in buildings, and while research has shown that these incidents are often related to the architectural design of stairways, stair safety remains difficult in practice. This is because knowledge of stairway design and the effectiveness of stair safety standards has been limited or within the profession of architecture. As a result, architects are experimenting with innovative designs that may increase the risk of tripping, slipping and falling on stairs. Steps to closing this knowledge gap and improving stair safety include assessments of design practices, identification of potential risks, and education on applying inclusive design thinking to stairways.

This thesis examined contemporary practices in stairway design and their effects on the behavior of stair users. A review of the professional literature identified innovative stairway design features related to stair safety. Two potentially hazardous features were identified for assessment in the real world: glass stair treads and interactive sound. Observations of stair use were collected at five different stairways in public buildings. The chosen design features were present in three of these stairways, and the other two stairways were constructed in a conventional manner. The incidence of unsafe stair use and key behaviors on the stairways were documented and compared.

The results showed that the glass stairway had incidents at a far higher rate than the conventional stairway. The rate of incidents in the interactive stairways was virtually the same to those in the conventional stairways. The findings suggest that research

attention should be given to glass stair treads. Interactive sound needs to be studied in more depth to determine if the perception of hazardous conditions leads to more caution or if the sound features cause people to pay more attention and avoid hazardous behaviour. The research also demonstrates that more assessments of stairway designs in use can help identify best practices and additional gaps in knowledge for the design of stairways.

This thesis provides architects and researchers insights into identifying stairway design hazards and evaluating their effects on stair users. While there are many other issues in the design of stairways that require research attention, this research provides a method to complete further field assessments and offers suggestions for future work on stair safety.

Chapter 1

1. Introduction

1.1. Research Aims

Stairway design can reduce the inherent risks of tripping, slipping, and falling that are present in all stairways (Archea, Collins, & Stahl, 1979; Templer, 1992). While the effectiveness of stairway design standards is typically investigated by an expert witness in litigation where a fall on stairs had occurred and determining fault is needed for the case (Cohen, 2000; Cohen, LaRue, & Cohen, 2009), fall risk assessments before "accidents" occur are limited. Similarly, research studies assessing the safety of stairway designs departing from convention that are not addressed by safety codes are limited. This thesis is aimed at investigating the role of evaluating design features and identifying potential hazards in contemporary stairway design practices and how this information can be used in research and practice to improve stair safety.

1.2. Stair Safety Background

Stair research in the United States has grown over the last 40 years due to greater awareness of the risks stairways pose in buildings. In 1973, the U.S. Consumer Product Safety Commission (CPSC) reported that stairways ranked at or near the top of the priority ranking of hazardous products and environments (Templer, 1979). Following this report, numerous studies examining stairway falls found that certain design features were related to more stairway incidents, such as stairways with irregular step dimensions and stairways that expose the user to visual distractions (Carson et al., 1978; Archea et al., 1979). These reports have established that stair safety could be improved by avoiding the

use of design features that have been associated with errors in gait and visual attention whenever it is possible.

While design is the most commonly cited reason for stairway falls, other reasons cited include user behavior and poor maintenance (Archea et al., 1979; Templer, 1992; Roys, 2001). User behaviors include running, using electronic devices and carrying things that distract the user's attention from the task of climbing stairs. Poor maintenance includes defective stair features, loose floor covering, and countermeasures intended to mitigate the effects of other causes of falls, e.g. peeling of non-slip applied surfaces. While these two risk factors can be controlled by injury prevention programs aimed at increasing awareness of safety actions which can be taken by stair users (Roys, 2001), the risks may always be greater for people with physical, sensory, and cognitive limitations. These include age-related conditions that can affect stepping and gazing patterns.

The user's perception of stairway features is essential for accurate foot placement (Archea et al., 1979; Templer, 1992). Perception of the stairway is achieved through visual scanning of the stairs and steps which requires people to maintain a certain level of attention throughout the entire flight of stairs (Hollands & Zietz, 2009; Miyasike-daSilva & McIlroy, 2012). However, due to certain design of stairways and the nature of human behavior and everyday situations, the focus of the user's visual attention often switches back and forth between the stairs and the surrounding, especially in places where views are present. Video recordings of stair users show that missteps and other errors in gait often occur when people turn their gaze away from the stairway (Archea et al., 1979). This suggests that shifting of visual focus increases perceptual errors, thus, stairways should be designed in a way that draws the user's attention to important features of stairways, rather than to any event or activity within the space. While focusing visual

attention to the stairway is important for safety, persistent gaze toward the stairs can also be an indicator of perceived hazards. When hazards are obvious, stair users pay closer attention to the task of negotiating the stairway.

The body of research has contributed to the code requirements of stairway design in the U.S., namely the International Building Code (IBC) which meets or exceeds the accessibility requirements of the Americans with Disabilities Act of 1990 (ADA) and the national consensus standard on accessibility (ICC, 2009). This has made stairways serving as accessible means of egress in public buildings safer today. But, these codes and standards are not applicable to stairways that are not required for egress. With few exceptions, the IBC requires only two means of egress in buildings (ICC, n.d.), which means that stairways in any given multi-story building that are not required means of egress may have design features that would be considered hazardous in the research literature, such as open risers and inadequate handrails. Furthermore, many unusual features are being incorporated into stairways that are unregulated, e.g. glass stair treads, interactive sound and light, treads at acute and obtuse angles, etc.

Stairway falls continue to be a major public health problem that results in human, economic, and social losses. In the U.S., falls on stairways account for 1,900 deaths (NSC, 2011) and 1.3 million hospitalizations per year (Pauls, 2011). A stair-related injury requiring hospital treatment is likely for every 1,766,000 flights of stairs climbed (Pauls, 2013). The 2013 annual cost to society for these injuries is 100 billion dollars in medical and litigation expenses which far exceeds the cost of stairway construction (Pauls, 2013). Although the majority of these falls (90%) occur in homes (Pauls, 2011), falling in public settings is also part of the problem (Cohen et al., 2009). This problem is known to exist not only known in the U.S. but also in many other countries including Canada (Pauls,

2011), the U.K. (Roys, 2011), Japan, and Sweden (Templer, 1992; Scott, 2005). As a global issue, stairway fall prevention efforts are clearly warranted.

1.3. Stairway Design Assessments

Stairway fall prevention efforts should include stairway design assessments which can be done in a laboratory setting or in the field. Laboratory research is most effective for studying differences in stairway design systematically using powerful data collection techniques. Field research can yield more realistic observations of the user's behavior and offer more reliable information about the impact of stairway design on incidents under real world conditions. Previous field studies have used video cameras to capture observations of stair users and their behaviors (Templer, Mullet, Archea, & Margulis, 1978; Archea et al., 1979; Cohen, 2000). This method allows researchers to replay incidents repeatedly to better understand the multi-faceted causes of slipping, tripping and falling. Stairway incidents are difficult to analyze based on direct observations alone as they occur quickly, and many factors, including the user's behavior and environmental components, are involved (Scott, 2005).

The earlier video-based observation studies, however, have been limited because of the technological constraints and high costs of video recording at the time. Moreover, older cameras were large and obtrusive. Today, video recording is more cost effective and less intrusive due to miniaturization and the ubiquitous use of electronic devices with video capabilities that can be used more easily. Field work risk assessments of both existing and newly constructed stairways using video observations can therefore be quick, easy, and cost-effective. These studies can provide supporting information on stairway design features that should be studied further in the laboratory.

1.4. Research Design

The objective of this thesis is twofold: First, to investigate contemporary practices in stairway design and, second, to examine the effects of innovative stairway design features on user safety. Previous research has mainly focused on conventional stairway design features, and few studies have explored the roles of behavior in stair safety. This research will focus on innovative stairway designs that are not addressed by safety codes and the user's behavior in order to better understand the factors affecting stairway falls. This thesis will address the research objective by exploring the following research questions:

- What are the current design practices and knowledge needs for stairway design?
- What can the behavior of stair users tell us about the effectiveness of design?
- How can stairway design assessments be used in research and practice to improve stair safety?

A review of the professional literature identified innovative stairway design features related to stair safety. Two potentially hazardous features were identified for assessment in the real world: glass stair treads and interactive sound. Observations of stair use were collected at five different stairways in public buildings. The chosen design features were present in three of these stairways, and the other two stairways were constructed in a conventional manner. The incidence of unsafe stair use and key behaviors on the stairways were documented and compared.

The principal outcomes of the thesis are (a) to identify aspects of contemporary stairway designs that may create barriers to safe stairway use, (b) to develop a low

cost, easy to implement method for identifying potential stairway hazards and (c) to facilitate ideas on how stairway design assessments can be used in research and practice to improve stair safety. While there has been a great deal of interest in encouraging stair use on both architectural and policy levels, much less emphasis has been placed on stair safety. These studies would be warranted simply because a higher frequency of stair use, for any reason, increases the exposure to risks of tripping, slipping and falling.

This thesis provides architects and researchers insights into stairway design hazards and evaluating their effects on stair users. Stairways are one of the most dangerous parts of the built environment, and they are present in all multi-story buildings. Increasing awareness of unsafe stairway design practices contributes to promoting the design of safer buildings that can be used by all people. While there are many other issues in the design of stairways that require research attention, this research provides a method to complete further field assessments and offers suggestions for future work on stair safety.

1.5. Chapter Summaries

The thesis will address the research aims in three research papers (chapters 2, 3, and 4) which comprise the major portion of this thesis. These chapters were written separately and therefore will have overlapping introductory material. Chapters 3 and 4 describe field observational studies that share the same methodology, thus the methods and limitations of the research discussed in these chapters will overlap as well. References relevant to each chapter are presented at the end of each chapter. The final chapter presents conclusions and implications for further work.

The research is organized within the following chapters:

- Chapter 2 describes an analysis of contemporary stairway designs shown in a leading architectural professional journal, *Architectural Record*, to provide an understanding of stairway hazards and the safety issues.
- Chapter 3 assesses the safety of an innovative stairway in an Apple Retail Store by observing the behavior of stair users and identifies issues that should be studied in a laboratory setting.
- Chapter 4, similar to the previous chapter, assesses the safety of interactive stairways through observational studies and identifies concerns for this trend.
- Chapter 5 summarizes the contributions of this thesis and outlines future directions for research on stair safety.

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Chapter 2

2. Stairway Design Practices

2.1. Abstract

This paper describes an evaluation of stairway designs shown in a leading architectural professional journal. A uniform set of criteria was used to evaluate each stairway as either safe or unsafe, and the frequency of visible stairway hazards was tabulated. A total of 855 stairways were found in *Architectural Record* feature articles and advertisements over an eleven-year publication period (2000-2010). Seventy-five percent of the stairways had at least one visible stairway hazard. The three most common were missing and/or inadequate handrails, low visual contrast on tread edges, and excessively long stair runs. The high prevalence of stairway hazards in the professional literature indicates a need for improved professional education on safe stairway design.

Keywords: Stair safety, stairway design, current practices, hazards, evaluation, architectural professional journal, education.

2.2. Introduction

Designing stairways is a ubiquitous part of architectural design. By today's standards, stairways should be as safe and usable as possible for able-bodied people of all ages and abilities. Although this approach should be a prime consideration in the design process, stairway design practices are lagging behind the knowledge available (Steinfeld & Maisel, 2012). In the United States, building codes specify only the minimum level of safety for accessible means of egress stairways in new and renovated commercial

buildings, and less stringent requirements are applicable to monumental stairways, or those that are not required for egress.

Stairway falls are a leading cause of unintentional injuries in buildings that results in human, economic, and social losses. This is the case not only in the U.S. (Pauls, 2011) but also in many other countries including Canada (Pauls, 2011), the U.K. (Roys, 2011b), Japan, and Sweden (Templer, 1992; Scott, 2005). As a major public health issue, stairway falls have been well documented (Archea, Collins, Stahl, 1979; Templer, 1992). Their major causes include user behaviors such as running, using electronic devices and carrying things that distract the user's attention from the task of climbing stairs, as well as the user's abilities related to cognition, vision, and gait that cause people to misjudge the conditions of the stairs and misstep. Poor maintenance is another cause of falls, including defective stair features, loose floor covering, and countermeasures intended to mitigate the effects of other causes of falls, e.g. peeling of non-slip applied surfaces. The third major cause of stair-related injuries is poor design and construction of stairways that affect the user's gait and visual attention.

Despite advances in knowledge of stair safety and usability, unsafe stairway design practices are still shockingly common. A scan of stairway images across a broad spectrum of media, including popular professional journals, will uncover many recently constructed stairways with noticeable and well known safety hazards. The stairways that are located in the U.S. do not even meet current codes, yet they were somehow built and published as exemplars of architectural practice. This suggests that many architects, code officials, and the architectural press are either unaware of the inherent risks of stair use, or choose to ignore good stair safety practices.

The purpose of this study was to investigate current practices in stairway design as featured in the architectural press, assess the degree to which safe design practices are present, and identify issues that have not yet been addressed in stair research. The paper concludes with a discussion about how safe stairway design can be supported by professional education.

2.3. Methods

2.3.1. Journal Sample

Images of constructed stairways in *Architectural Record* feature articles and advertisements from 2000 to 2010 were evaluated. This journal was chosen because it is the oldest and most established professional architectural journal in the U.S. which can provide a sample of stairway design ideals and practices.

The study builds upon the work of a previous class project by twenty-one graduate students in an ergonomics course at the University at Buffalo Department of Architecture. The class project consisted of stairway design evaluations performed by seven teams, with each team using their own method of data collection and analysis. The results indicated that a more controlled study would be fruitful for identifying a gap in knowledge translation from research to practice in safe stairway design. Using the student work to provide initial insight into stairway design practices, a new method was developed to scan and evaluate every stairway shown in *Architectural Record*. The study was then repeated by the author.

2.3.2. Checklist Development

Based on the student work and the research literature, a hazard checklist was developed to identify and record stairway hazards (see Figure 1). A reasonably safe and usable stairway is regarded in the literature as one that meets all current safety standards for railing, step geometry, and visibility of stairs (Pauls, 2013). Thus, the checklist was divided into those three areas of design, and the common design flaws for each category were listed under. The fourth category included other safety factors related to the entire stairway. Although the primary focus was to identify stairway design hazards, the setting for each stairway, i.e. public or residential, was also recorded.

Railing
Handrails not fully extended
Handrails too large or thin
Inadequate balustrades
Non-existent or inadequate handrails
Step geometry
High/low riser to tread width ratio
Irregular riser height/tread depth
Narrow stairway width
Short tread depth
Visibility
Distracting pattern on steps
Low contrast on tread edges
Open or see-thru risers
Poor lighting
Other hazards
Inconsistency within the top 3 or bottom 3 steps
Flight too long (over 15 risers without a landing)
Oblique stair without adequate handrail
Obstruction on stairs

Figure 1. Stairway design hazard checklist.

2.3.3. Procedure

Every page in each issue of the journal was manually reviewed for images of stairways. Images that were readily discernible were documented using a scanner and digital camera. Small prints that lacked sufficient details to evaluate were excluded. Each image was cropped and inserted into a page template using graphic representation software. Evaluations were based solely on image content, and they were guided by two principles: if a stairway image showed at least one condition listed in the criteria for unsafe stairway, then it was classified as unsafe; if the image did not show any condition listed in the criteria for unsafe stairway then it was classified as safe. Every unsafe condition was recorded on the hazard checklist in spreadsheets, and the frequency of stairway hazards was tabulated.

2.4. Results

In this section, the results of the study are summarized using references to U.S. building code standards and the research literature in order to better address and understand the risks of each stairway hazard found. This section summarizes only the most common stairway hazards that were found in the study.

2.4.1. Stairway Design in the Professional Media

Eight hundred fifty-five stairways were found that met the screening criteria. Of these, 72% were public stairs and 28% were residential stairs. Seventy-five percent of all stairways had at least one noticeable stairway hazard and were classified as unsafe (see Table 1). Of these, 50% were public stairs and 25% were residential stairs, which means that only 3% of residential stairs were free of visible hazards (see Figure 2). It should be noted that journals like *Architectural Record* focus primary on high-end residences.

Table 1. Summary of stairway evaluations by year ($N = 855$ stairways).

Year	Safe	Unsafe	Total
2000	22 (25.6%)	64 (74.4%)	86
2001	18 (25.7%)	52 (74.3%)	70
2002	16 (16.3%)	82 (83.7%)	98
2003	24 (29.6%)	57 (70.4%)	81
2004	23 (26.4%)	64 (73.6%)	87
2005	14 (20.3%)	55 (79.7%)	69
2006	23 (27.1%)	62 (72.9%)	85
2007	21 (27.6%)	55 (72.4%)	76
2008	23 (27.4%)	61 (72.6%)	84
2009	16 (22.2%)	56 (77.8%)	72
2010	10 (21.3%)	37 (78.7%)	47
Total	210 (24.6%)	645 (75.4%)	855

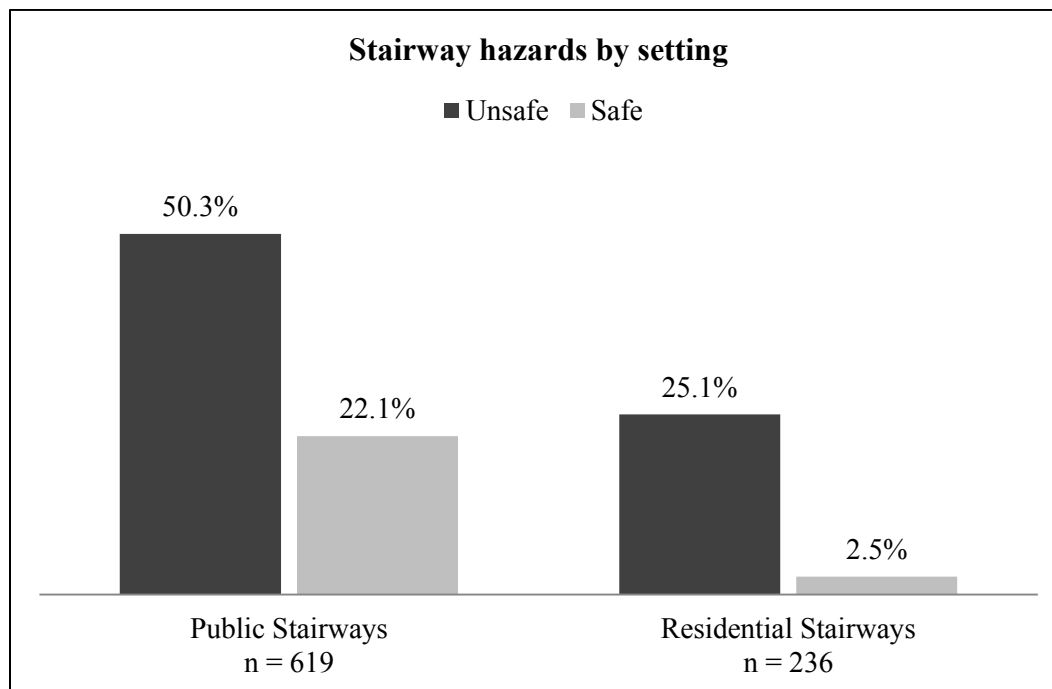


Figure 2. Stairway hazards by setting ($N = 855$ stairways).

The most frequently observed category of safety hazards was the railing, comprising 40 percent of the all stairway hazards documented (see Table 2). Stairway design factors affecting a person's visual perception were second most problematic (29%). Irregular stair dimensions and other general hazards were each found in at least 14 percent of the stairways. It should be noted that without any way to physically measure the stairways, the study method was a very crude measure, based on obvious anomalies rather than precise measurements and thus the results are probably underreporting the frequency of stairway hazards, e.g. irregularities in stair geometry.

Table 2. Stairway hazard categories ($N = 1,207$ stairway hazards).

Stair Categories	Frequency	Percent
Railing	482	39.9%
Step geometry	198	16.4%
Visibility	353	29.2%
Other Factors	174	14.4%

The three most common unsafe stairway design practices were missing and/or inadequate handrails (41%), low visual contrast on tread edges (19%), and excessively long stair runs (16%) (see Figure 3). While the vast majority of the stairways had one (45%) or two (31%) stairway hazards out of the sixteen that were identified for this study (see Table 3), the number of hazards should not be used as a means to rate stair safety since a misstep or a fall can occur as a result of one grievous condition or several minor hazardous conditions.

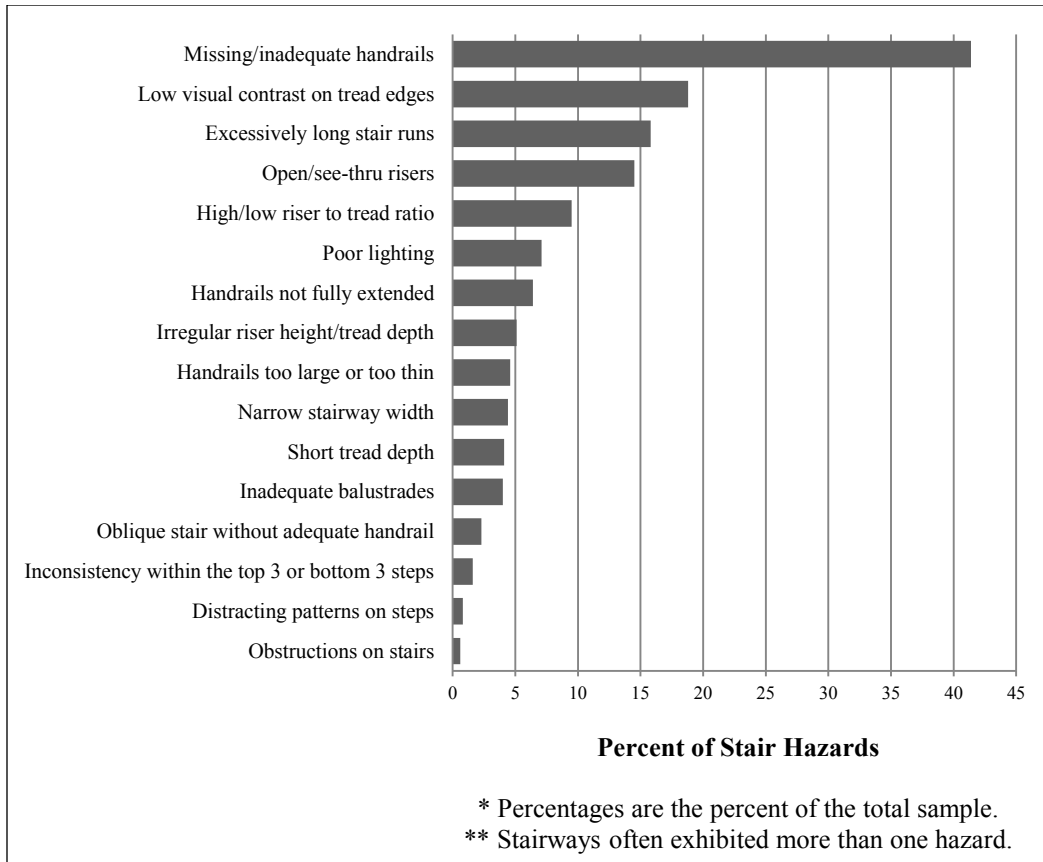


Figure 3. Most common stairway hazards in *Architectural Record* (2000-2010).

Table 3. Unsafe stairways by number of hazards ($N = 645$ unsafe stairways).

Hazards	Count	Percentage
1	293	45.4%
2	200	31.0%
3	98	15.2%
4	42	6.5%
5	10	1.6%
6	2	0.3%

2.4.2. Stairway Hazards

2.4.2.1. Railing

2.4.2.1.1. Missing or inadequate handrails

Handrails serve multiple functions: visual cues to the stairway's presence, directional guidance, postural stability, fall mitigation, and to facilitate traversing either in ascent or descent since we tend to stay to the right on stairways in North America (Templer, 1992; Jackson & Cohen, 1995; Dusenberry, Simpson, & DelloRusso, 2009). Best practice recommendations include the provision of handrails on both sides of stairways.

The International Building Code (IBC) has exceptions to the requirement for handrails on both sides, notably residential stairs and spiral stairs; stairs on decks and patios are not required to have any handrails; a single elevation change at an entrance or egress door and changes in elevations of three or fewer risers within dwelling units also do not require handrails (IBC, 2009). However for elders and people with disabilities who require additional support to maintain balance, following minimum standards and taking advantage of exceptions like these can pose significant safety risks.

Although the handrail is probably the most important safety device for the user on a stairway, the study found that the most common hazard in stairway design practices was its absence and/or inadequacy. Forty-one percent of the stairways ($n = 354$)—nearly one out of every four stairways in the professional journal—met at least one of the following criteria: unprotected stairways at one or both sides, three or fewer steps that were potentially difficult to see or expect without handrails as visual cues, wide stairways without intermediate handrails spaced equally across the width, and non-continuous

handrails that were interrupted by newel posts within environments where releasing grip on the handrail might be hazardous.

2.4.2.1.2. Handrails were not fully extended

A basic principle of safe stairway design is that the handrail must be available for the user to grasp on the first step and maintain a grip all the way through the last step. Handrails are most heavily used at the top and bottom of stair runs (Templer, 1992) so these areas, including the landings, are where they are needed most. At landings, handrail extensions can help people identify the start and end of elevation changes, gain stability when mounting and dismounting stair runs, and make a safe transition in gait between landings and steps (Templer, 1992; Danford & Tauke, 2001; Bakken, Cohen, & Abele, 2007).

U.S. building codes require handrails to be both continuous for the full length of each flight and extended at least 12 inches (305 mm) beyond the top and bottom riser, plus the width of one tread for the bottom extension. These extensions however are not required in dwelling units, assembly areas, the inside turn of stairways, and in existing stairways where such extensions would be an obstruction (IBC, 2009).

In this study, which consisted mostly of new or substantially remodeled building projects, 6.4% ($n = 55$) of the stairways had inadequate extensions of handrails. Although this part of the evaluation was intended to focus on handrails that did not extend across landings ($n = 10$) where there was an opportunity to do so, the study found more cases ($n = 35$) where handrails were truncated before even reaching the top or bottom riser (see Figure 4). The lack of handrails at these locations can be a more significant contributor to accidents since the majority (70%) of stairway incidents occur at the ends of stair runs as



Figure 4. A stairway with a thin truncated handrail, inadequate balustrades, and low visual contrast on the tread edges (Photographer: Toshiyuki Yano).

people modify their gait and adapt to changes in view, illumination, route directions, and floor surface while entering and leaving stairways (Templer, 1992).

2.4.2.1.3. Handrails were too wide or too thin

After losing balance on the stairs we search for support in an attempt to arrest a fall by reaching out and grasping a handrail (Templer, 1992). Handrail shapes that are too wide or too thin are not ergonomically designed to be grasped firmly and thus may not be effective during falls. A round handrail between 1.25 inches (32 mm) and 2 inches (51 mm) in diameter is generally accepted as the best shape and size for gripping because it provides a "power grip" in which the thumb can touch the fingers in the shape of the letter C (Maki, Perry, & McIlroy, 1998; Bakken et al., 2007; Dusenberry et al., 2009). Narrow or other shapes that require a "pinch grip" are not recommended (Maki, 2011).

Handrails were visibly too wide or too thin in 4.6% ($n = 39$) of the stairways. Rectangular shaped handrails made of metal or wood in 2x4 or 2x6 flat configuration were common types of poor handrail design. Railings with smaller cross-sections were used in minimalist designs, probably for their reduced obtrusiveness, as seen previously in Figure 4. As with irregularities of step geometry, the study methods did not allow measurement of handrails; the study focused on only grievous conditions so this deficiency is probably underreported.

2.4.2.1.4. Missing or inadequate balustrades

Balustrades have more leeway for decorative patterns, for instance custom wrought iron railings, but it must be remembered that they are intended to protect open sides of stairways. Open spaces between balusters that are greater than 3.5 inches (89 mm) are areas where a child's head could slip through or body parts could become caught during a fall (Archea et al., 1979). Large gaps under the bottom rail allow objects to slide or roll off the sides of stairways to areas below. Sharp edges of balusters pose risk of bodily injury, especially during a fall. Horizontal rails and other balustrade attributes that can be climbed also pose risks for children and even adults (Templer, 1992).

The balustrade was missing or inadequate in 4% ($n = 34$) of the stairways. The majority of these were in homes (67%) where the practice of omitting balusters was more common, additional evidence of a stylistic preference toward minimalism. In the simplest designs, only a railing was provided with no protective balustrade. Another variation on this theme was a railing with balusters spaced several stair treads apart and large enough for a person to easily fall through. This is also seen in the stairway in Figure 4 (on page 20).

2.4.2.2. Visibility

2.4.2.2.1. Low visual contrast on tread edges

The tread edge is a key attribute in stairway design that allows users to understand the elevation changes between steps, placement of the leading foot, and to establish and control their gait (Archea et al., 1979; Templer, 1992; Zietz & Hollands, 2009; Den Otter, Hoogwerf, & Woude, 2011). Stair users visually scan a stairway using both foveal and peripheral vision. Depending on the user's attentiveness and the complexity of the environment, people may either look at the stair edges continuously, or they may glance down to scan the stair periodically. Research demonstrates that they scan at least once every seven steps taken (Templer, 1992). In periodic scanning, stair users rarely look directly at the edges, perhaps because they are using more of their peripheral vision than foveal vision (Miyasike-daSilva, Allard, & McIlroy, 2011). High contrast edges could help make each step edge more visible even with periodic scanning.

The ADA accessibility guidelines (2010) advise architects and builders to provide visual contrast on tread edges mainly for people experiencing low vision, but this design practice can obviously benefit those with good vision as well (IBC, 2009). High contrast edges not only provide better cues in both the central and peripheral zones of vision but also prevent steps from appearing to blend together to create a dangerous illusion of a ramp (Templer, 1992).

The study found that low visual contrast on tread edges was the second most unsafe stairway design practice (19%) (see Figure 4 on page 20). A stairway painted completely white is an example of many stairways in the sample that were clearly designed to

emphasize aesthetics at the expense of safety. The use of materials such as glass and reflective surfaces without delineating the tread edges was also a common practice that could affect a person's visual perception of the stairs.

2.4.2.2.2. Open risers

There are two primary types of step and riser design: closed riser stairs (required within means of egress) and open riser stairs (not permitted for egress). Closed risers prevent feet and canes from accidentally slipping under treads, and they keep children, pets and objects on stairs from falling through (Templer, 1992). The solid barriers between treads also block distracting views in the background behind the stairs that may draw the user's attention away from the steps during ascent and cause falls. Although open risers provide a dynamic and exciting stairway form, they are allowed only if a 4 inch (102 mm) sphere cannot pass through openings (IBC, 2009).

The fourth-ranked unsafe stairway design practice (14.5% or $n = 124$) was the use of open risers where visual distractions behind the stairway were likely to occur due to overstimulating views in the background as can be seen in Figure 5. Over 50% ($n = 70$) of these stairways were in residential settings where children and elderly people are especially vulnerable to slips and falls. It was noted that in many of these cases, riser openings appeared much larger than is allowed, possibly exceeding the 4 inch sphere rule.



Figure 5. Visual distractions in an open riser stairway (Photographer: Kouji Okamoto / Techni Staff).

2.4.2.2.3. Poor lighting

Lighting affects our ability to perceive steps, railings, and hazards on the stairway (Templer, 1992). Studies examining light as a risk factor show a higher incidence of missteps and falls on stairways with lower illumination levels. Carson et al., (1978) found that incidents were twice more likely at 2 foot-candles (22 lux) of light than at 8 foot-candles (86 lux) (cited in Templer, 1992). Hamel et al., (2005) found that older adults had missteps in dark stairways because they did not lift their legs higher away from the steps while descending the stairs as young adults did. Similarly, Kasahara et al., (2007) found that under low illumination older adults restricted their eye movements and visual scanning patterns to foveal regions because they needed more time to focus on the steps directly ahead, and this caused them to disregard visual information in the periphery.

Current lighting recommendations for stairways range from 10 to 20 foot-candles (108 to 215 lux) (IES, n.d.). Only 1 foot-candle (11 lux) is required by the IBC (2009) for accessible egress, which is not enough illumination for the aging eye according to the IES. Templer argues that a minimum of 8 foot-candles (86 lux) may be just enough (1992). Good stairway lighting should also include even illumination on the handrails and walking surfaces so that shadows do not fall on the stairs as well as indirect illumination that does not shine into the user's field of view and cause glare (Templer, 1992).

In this study, 7.1% ($n = 61$) of the stairways were noticeably dim or lit unevenly where other hazards were present. These stairways are especially dangerous for older adults who may not be able to perceive stairway hazards and adapt to dark stairways as well as young adults as was demonstrated by the Hamel and Kasahara studies. Again, it was impossible to actually measure the illumination in the photographs. Moreover, photographers may carefully illuminate their subjects during professional photography so the frequency of this hazard is probably underreported as well.

2.4.2.3. Step geometry

2.4.2.3.1. High or low riser to tread ratio

The slope of the stairway should allow comfortable walking gaits. Sometimes, however, the stair pitch is skewed toward steeper slopes in order to fit the stairway in a building or to increase the economic efficiency of the building plan, i.e. more rentable or salable space. But, high risers cause missteps (Johnson & Pauls, 2010). People must use a higher leg lift and exert more strength to raise their whole body up and forward to ascend steep stairs. In descent, control of balance is more difficult as people shift their weight forward and downward for longer distances while balancing on one leg in each footfall (Templer,

1992). In shallow stairways, the large treads force people to overextend their gait or to take each step with both feet, which result in an awkward walking rhythm.

Research shows that the optimum ratio for stairways is a vertical rise of 7 inches (178 mm) combined with an 11 inch (280 mm) tread depth, which is also known as the 7-11 design rule for accessible stairs. This geometry is based on a study that analyzed 63,000 ascents and descents on a variety of stairways and found fewer incidents occurring on 7-11 stairways than on other geometries (Templer 1992) therefore it is believed to help reduce the risk of falling. The building code standard for spiral stairways, however, differs and do not meet the 7-11 step geometry. Risers within spiral flights can measure up to 9.5 inches (241 mm) and treads can have a 7.5 inches (191 mm) minimum clear tread depth measured 12 inches (305 mm) from the narrower edge (IBC, 2009).

This study evaluated only excessively steep (64) and shallow (17) stairways and found that 9.5% ($n = 81$) of the stairways met the screening criteria, ranking fifth in unsafe stairway design practices. Since it could not be determined whether stairways were within the 7-11 code, this result is also probably underrepresenting the frequency of non-compliant stairways.

2.4.2.3.2. Irregular riser height or tread depth

Another basic principle of safe stairway design is that the riser and tread must be uniform for every step in a stair flight. People tend to expect well built (and safe) stairways and thus uniformity in their form, an expectation that leads to low attention to the steps while climbing stairways (Templer, 1992). Unfortunately, dimensional irregularities are common mistakes made during construction, varying typically between 5/32 to 1/4 inches (4 mm to 6 mm) (Roys, 2011a). In addition to the quality of stair construction, a

continuous run of equally shaped treads reduces the risk of missteps by allowing people to have a more consistent gait pattern, as opposed to forcing alterations of gait while climbing on rectangular and winder shaped treads in the same stair flight for example.

It is well known that dimensional irregularity of steps is a leading cause of stairway falls (Jackson & Cohen, 1995; Cohen et al., 2009; Johnson & Pauls, 2010). To help counter the problem, building code specifications for accessible stairways require uniform risers and treads where the largest riser/tread minus the smallest riser/tread in a flight of stairs cannot exceed 3/8 inches (9.5 mm) (IBC, 2009). But, this tolerance may be too great. Research shows that even a slight irregularity of as little as 1/4 inch (6 mm) can interfere with the user's gait (Johnson, 2011).

Nearly 5% ($n = 44$) of the stairways in the sample had obvious irregularities in step geometry—17 (39%) straight flights and 27 (61%) curved flights. In this study, the use of rectangular treads in combination with winder treads was also considered a relevant hazard where other stairway design deficiencies were present, such as a narrow stairway width as seen in Figure 6. This stairway, located in a residential setting, provides a familiar environment in which people are likely to pay less attention to the changes in tread size. As with other criteria, the study was limited in that it did not actually measure risers and treads so it is probably underrepresenting the frequency of dimensional irregularities.



Figure 6. A narrow stairway with variation in tread size (Photographer: Michael Moran Photography).

2.4.2.3.3. Narrow stairway width

The clear width between walls, railings or the edges of the tread should accommodate the expected traffic flow and reach ranges for handrails (Levine, 2003). People need adequate space on stairways to move safely and comfortably including space for their body ellipse, pacing zone, sensory zone, and buffer zone (Templer, 1992).

The minimum code requirement for straight flight stair widths is 36 inches (914 mm) for areas with an occupant load of 50 or less and 44 inches (1118 mm) for 50 or more people (IBC, 2009). Templer (1992) argues 38 inches (965 mm) is needed for minimal comfort; 56 inches (1422 mm) allows people to walk side-by-side in heavy clothing; but, a 69 inch (1753 mm) stair width includes clearance between heavy clothing and tolerance for tracking error and thus is most comfortable. Codes allow spiral stairways to be narrower,

26 inches (660 mm) in width (IBC, 2009), but these stairways do not provide the standard 11 inch (280 mm) minimum going at the walking line. The minimum spiral stair width would have to be 6 feet, 9 inches (2.06 m) wide to provide adequate tread depth at the inside walking line (Templer, 1992).

The study found that 4.4% ($n = 38$) of the stairways were narrow—24 (63%) of which were without handrails, and 11 (29%) had winder treads. Narrow stairways without handrails can create problems in implementing handrail retrofits in the future. For example, adding handrails to the open riser stairway in Figure 5 (on page 24) may not be possible without creating discomfort since handrails take up at least 3 inches (76 mm) on each side of the stairs (Templer, 1992), and this would reduce the effective width of the stairs even more. A narrow stairway width in spiral configurations forces the user closer to the inside radius where the tread becomes too small for safe walking, as seen previously in Figure 6.

2.4.2.3.4. Short tread depth

Slips due to overstepping treads in descent are the most frequent type of stairway falls (Bakken et al., 2007; Johnson & Pauls, 2010). The risk of overstepping is increased by treads that are too narrow to accommodate the length of the foot. This condition is often found along the inner radius of winder or "pie-shaped" treads in curved stairways, which should be avoided whenever possible since it is not as safe for foot placement as straight treads, although the outer tread can provide a safer pathway.

The building code requires an 11 inch (280 mm) tread as the minimum effective depth for accessible stairways in public buildings (IBC, 2009). Although this is the optimum tread

dimension for stairs, treads in residential buildings are currently allowed to be smaller, with a minimum tread of 10 inches (254 mm) (IRC, 2009). Treads within spiral flights can be even smaller with a 7.5 inch (191 mm) minimum depth measured 12 inches (305 mm) from the narrower edge (IBC, 2009).

Although the study methods did not allow measurement of the steps, the study found that 4.1% ($n = 35$) of the stairways had treads that were clearly too narrow for proper foot placement. The majority (77%) of these were in winding and spiral configurations and in both public and home settings where the risk of slipping or overstepping were identifiable at the inside area of wedged treads, as seen previously in Figure 6 (on page 28). The study found that all curved stairways in home settings ($n = 27$) had short tread depths.

2.4.2.4. Other hazards

2.4.2.4.1. Excessive length of stairway run

A reasonably safe stairway should consist of at least three risers, so that it is noticeable and people do not accidentally walk into it (Templer, 1992); but, it should also not have too many steps without a landing since the risk of falling on stairways is greater the longer the duration of exposure. Moreover, excessively long flights require greater energy expenditure over a longer time of exertion which creates sudden loss of balance for older adults, people with arthritis and those with low stamina who need to stop and rest periodically. There are psychological factors to consider as well. Ascending and descending stairways are daunting tasks for people with physical or mental limitations. A long continuous run of steps can add to the problem and contribute to fear of falling, which is associated with frailty, reduced mobility, impaired gait and balance in older people (Tiedemann, Sherrington, & Lord, 2007).

Although the IBC (2009) does not specify the number of steps in a flight, it is recommended by the National Safety Council (NSC) that a landing be provided at every tenth or twelfth tread (Reese, 2009). Older people in a focus group study have reported that they can negotiate twelve steps in between landings as the maximum number of steps (Ormerod, 2011).

The study found that excessive stair run length was the third most unsafe stairway design practice (15.8% or $n = 135$). In designing the criteria, the study limited the number of risers to fifteen for an acceptably safe stairway, and therefore stairways exceeding the criteria were deemed excessively long and unsafe such as the one shown in Figure 7, which has a total of twenty two risers.



Figure 7. A stairway with an excessive stair run length (Photographer: Elizabeth Felicella).

2.5. Discussion

The scan of current stairway design practices revealed that practicing professionals in the U.S. and in many other countries are not applying the knowledge available on stair safety in actual practice, except where the building code requires practices consistent with that knowledge (primarily in the U.S). Although standards lag behind the science, it also does not prohibit, in most cases, the adoption of best practices, for example, contrasting tread edges and easy to grasp handrails.

2.5.1. Research Questions

The systematic research raised some questions for future investigation. Open risers was of particular interest because the use of this feature is almost entirely based on aesthetic considerations. There is no practical reason for using open risers other than saving material, but the materials used on most open riser stairways clearly indicate that cost was not a major consideration in their design. Thus the adoption of this feature indicates that safety is not a major consideration for the design of stairways, particularly in the U.S. where the architect has fewer code requirements to address for monumental stairways outside required means of egress and residential stairways. In this study, open risers were present in designs that created the appearance of light, floating stairways, although the resulting spatial transparency and exposure to extraneous views could distract the user's foveal vision. An important research question that has not been adequately addressed is the influence of open risers on visual performance and gait during stair walking.

Templer suggested that long stairways are safer because they cause people to use more attention on the stairs (1992). In other words, in a short stair run, the user may glance at the stairs only at the transition at top and bottom but not in between, but, on a long

stairway, they will glance at the steps one or more times in addition. Is this hypothesis correct? Research on how users distribute their attention in relation to stairway length would be useful to determine optimum stair runs from an attention perspective.

Although winder treads are inherently more dangerous than straight treads, they are favored by architects because they can be used to create sinuous stairways, as well as to fit stairways in small spaces. With a particular interest in visual performance of stair users, an important research related question is the impact of winder treads used in places where distractions cause people to turn their attention away from the stairs that are changing rapidly in size and shape as they descend or ascend.

New technologies allow the use of unusual materials for stair treads. Glass, in particular, was identified in this study as a growing practice ($n = 21$ or 2%) that reduces visibility of the tread edge (see Figure 8). Although nonslip treatments are available for glass used as a walking surface, where users are likely to track water in during bad weather, these treatments may not be adequate. Research is needed to determine if glass is a safety hazard due to camouflage of tread edges or reduced friction between shoes and treads, especially under wet conditions.



Figure 8. A stairway with glass treads (Photographer: Roy Wright Photography, Inc.).

2.5.2. Stair Safety Education

The high prevalence of stairway designs that include features considered hazardous in the research literature indicates that many architects are either unaware of the risk factors associated with stair use, or they choose to ignore good practices to achieve other goals, e.g. aesthetic triumphs and attention by their peers (e.g. designing the lightest looking stairway ever). This suggests a need for improved professional education on stair safety both in professional curricula and in continuing education.

Educational programs targeted to stairway design and the behavioral issues would contribute to promoting the adoption of safer practices. Education is critical to increase awareness of the legal risks facing both architects and clients and garner interest in safer designs by demonstrating the severity of the dangers posed by design. This could be

implemented at various professional levels. For example, codes and standards should be incorporated into school curricula to ensure that student work demonstrates the ability to recognize and also design safe stairways, not only to meet the codes but to facilitate best practices beyond minimum requirements. Continuing education on the latest knowledge about stair safety that is not included in safety codes would not only inform practicing professionals, but also encourage them to develop new ideas for designing safe and attractive stairways. These activities could shed light on lesser known, but important safety issues, including the impact of individual differences on gaze behavior, placement of attractive features in stairway surroundings, and optimal handrail design. Furthermore, given that a significant number of stairways featured in the articles scanned were in the U.S. and did not meet building codes, continuing education would be warranted in the building regulatory community. This could clear any misconceptions about stair safety code requirements both on the part of the professionals and the code officials.

In addition to finding that only one-quarter of the stairways were reasonably safe, only one feature article about stair safety was found in the literature scan of eleven years. This indicates that communication about safety in the design of stairways is minimal in professional media. Clearly, *Architectural Record* featured monumental stairways and buildings that have unusual form features, not the prosaic stair towers hidden away in the bowels of buildings and the stairways in the buildings used by most building users. One could argue that the vast majority of stairways meet code requirements and are relatively safe. But, considering stairways are important parts of architectural design and given the liability risks associated with their use, it would be reasonable for architectural journals to feature more articles about good stairway design practices or at least provide some criticism of the unsafe stairways featured in their articles. These articles could also focus

on the health benefits that stairs provide building users. Such content could influence architects and builders to design and build more carefully.

2.5.3. Limitations and Future Work

The results of this study represent stairway design practices in only one professional journal. *Architectural Record* focuses primarily on high-end buildings, especially in the residential sector of the building industry. A similar study of buildings not included in journals would be useful to find out if the findings here are widespread in practice. Another limitation of the study is that this professional journal may only include buildings that are designed by well-known or established architects who have more leeway to depart from conventional practice than the average architect. Other architects may be more knowledgeable and careful about safe design. Yet, the architects whose work are featured in the journals stand as role models for the profession and one may ask whether they should take that responsibility seriously. An analogy is the star athlete who takes performance enhancing drugs.

Although the study was carefully designed to maintain accuracy, the stairways were evaluated by a single researcher, thus the reliability of the method is still in question. Furthermore, the method has some significant limitations on access to content. Stairway images could have been misleading or distorted during professional photography and editing; details could have also been hidden due to camera angles. But, given the simplicity of the method used, the findings are probably an underrepresentation of the actual frequency of hazards in current stairway design practices.

The final set of evaluative criteria provided a standardized measure that can be used across various media, both other journals and other media. It will serve as a tool for future studies by students and researchers. For future work, the literature scan could be extended to learn more about the reader's perception of stairway designs. It may be useful to assesses the degree to which readers of professional journals can recognize unsafe stairway design features and whether, for the architects, it influences their own design practices, and for clients, their communications with architects and designers.

2.6. Summary and Conclusion

This study reviewed the safety of current stairway design practices as featured in *Architectural Record* over an eleven-year publication period (2000-2010) and outlined the most common hazards found in the buildings featured using references to U.S. building code standards and the research literature to better address and understand the risks. The study acknowledges that popular media, including professional journals, tend to feature buildings that are visually appealing or designed by well-known architects to attract more readership. But, the findings show that unsafe stairway design ideals and practices outweigh those that are safe, suggesting a need to improve stair safety education. The study identified design issues that have not been addressed adequately by research which provides directions for future work on stair safety. Finally, the study discussed how professional education and media could contribute to improving the attention practitioners give to stairway design. It is hoped that with education and awareness on stair safety, architects and designers will take more interest in designing safer stairways that at the same time are attractive and innovative. These goals are not mutually exclusive.

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Chapter 3

3. The Effects of Glass Stair Treads on Stair Users in an Apple Retail Store

3.1. Abstract

Stair safety is a top priority for building users in public buildings. Although stairways present fall risks and usability issues for people of all ages, architects are introducing innovative features into public stairway design that have many potential hazardous features. The purpose of this study was to assess the safety of an innovative stairway in an Apple Retail Store by observing the behavior of stair users and to identify issues that should be studied in a laboratory setting. A checklist for recording observations of stair use was developed. Pilot studies were conducted to determine the feasibility of direct observations of stair users using a video recorder and to identify issues of unsafe stair use for further investigation. A controlled observation study was then conducted in an Apple Retail Store with a glass stairway (GS) and a shopping mall with a conventional stairway (CS). The incidence of unsafe stair use and key behaviors (tread gaze, diverted gaze, and handrail use) on the two stairways were documented and compared. Incident rates were significantly higher on the glass stairway (6.2%) compared to the conventional stairway (0.7%). On the glass stairway, more users glanced down at the treads (GS: 87% vs. CS: 60%), fewer users diverted their gaze away from the stairs (GS: 55% vs. CS: 67%), and handrail use was higher (GS: 32% vs. CS: 25%). Walking on winding treads made of glass may be more dangerous than walking on conventional materials due to reduced visibility of the tread edge or reduced friction between shoes and treads. Laboratory research is needed to determine if glass treads present safety risks.

Keywords. Stair safety, stairway design, glass stair treads, winding stairway, assessment, observational studies, gaze behavior, visibility, flooring material.

3.2. Introduction

Stairway falls are a public health concern that the profession needs to consider. In the United States, stairways are a leading site of fall-related injuries, accounting for 1,900 deaths (NSC, 2011) and 1.3 million hospitalizations per year (Pauls, 2011). The 2013 annual cost to society for these injuries is 100 billion dollars in medical and litigation expenses which far exceeds the cost of stairway construction (Pauls, 2013). Although the majority of these falls (90%) occur in homes (Pauls, 2011), falling in public settings is also part of the problem (Cohen et al., 2009). A recent survey of problematic activities in public buildings found that using stairways was the top problematic activity out of 24 groups surveyed, making stairway design the top priority of end users in public buildings (Danford, Grimble, & Maisel, 2009). Knowledge for design of stairways is limited, however, which has resulted in difficulty identifying best practices and improving design guidelines (Steinfeld & Maisel, 2012). In the absence of evidence-based design guidelines, contemporary architects are experimenting with unusual stairway designs and different materials that may increase a person's risk of tripping, slipping or balance problems.

This study is part of a larger investigation of stair safety which includes a literature scan of design practices, additional observational studies and a laboratory research study. This study investigated the effects of a contemporary stairway design on stair users compared with those of a conventional stairway design. A stairway in an Apple store was selected for the study because it has unusual conditions that may increase the risk of falls

including a winding stair configuration, open risers, and glass walking surfaces. Among various stair configurations, winding stairways are considered more dangerous than straight stairways because the treads are tapered so that users are twisting their bodies and shifting their weight differently on the left and right foot as they ascend and descend. This pattern of walking puts stair users at a greater risk of losing balance during movements of body rotation compared to the gait patterns associated with straight stairs which typically do not require the user to twist their torso.

In addition, people tend to stay to the right on stairways in the U.S. therefore the effective tread depth is different going up than down on winder treads. Walking pattern is further differentiated by the direction of curvature. On a winding stair ascending in the clockwise direction, people tend to climb the steps along the inner radius of the stair where the tread is narrower and descend along the outer tread that is wider. Rising anticlockwise, people ascend at the wider end of the treads and descend at the narrower end; this direction of curvature is more dangerous for descent (the more dangerous direction) due to narrow treads. Furthermore, the risks associated with tapered treads may be greater in the Apple store due to the appearance of glass surfaces and the presence of distracting views through open risers and from the stairs towards merchandise and customers. Although research suggests that winding treads, due to the perceived risk of falling, demand the user's attention and thus people rarely look away from the stairs to attend to other views (Templer, 1992), the context and materials of the stairway in the Apple store may cause people to divide their attention too much between walking and looking.

Stair climbing is also affected by the physical properties of the tread material. Glass reduces visibility and detectability of tread edges that increases the likelihood of the user to misjudge steps and misstep. As a flooring material, glass tends to perform less well in

wet conditions since water reduces friction between shoes and treads. Moreover, the coefficient of friction recommended for stairways is intended to provide slip resistance for normal and steady gait and may not be adequate for fast gait or winding stairways where the user's body twists while walking (Templer, 1992). Although non-slip treatments are available for glass used as a walking surface, where users are likely to track water in during bad weather, these treatments may not be adequate because water is not absorbed by glass; water on treads may negate the effect of "non-slip" coatings and textures. The last problem is clearly known to the Apple store managers in New York City. Carpeting is installed on the glass treads and landings on days that have heavy precipitation.

There is currently no available research describing the use of glass treads in the design of stairways which indicates that there is little evidence to support this design practice. The purpose of this study was to assess the safety of an innovative stairway in an Apple store by observing the behavior of stair users and to identify issues that should be studied in a laboratory setting.

3.3. Methods

3.3.1. Hypotheses

The following hypotheses guided the research:

- **H1:** Walking on glass treads will increase tripping, slipping or balance problems in stair walking compared to treads constructed from conventional materials.
- **H2:** Diversions away from stair treads will lead to more serious consequences on glass stairways than on conventional stairways.

3.3.2. Exploratory Study

3.3.2.1. Protocol

The University Institutional Review Board determined that the research did not meet the definition of human subjects. We did not gain any personal information about people through intervention or interaction therefore no IRB approval was needed for the project.

3.3.2.2. Procedure

Two Apple stores, one on 14th Street (Apple store 1) and one on 5th Avenue (Apple store 2), in New York City were selected as the sites for observations because each site had a winding stairway made of glass that differed only in the direction of curvature. One of the research intents was to compare stair use between the two stairways, but the final study excludes stair use data from store 2.

Observational studies were conducted by the author at Apple stores 1 and 2 to determine the feasibility of direct observations of stair users using a video recorder and to confirm areas of unsafe stair use for further investigation. Video recording was selected as the study method because recordings could be replayed repeatedly for analysis purposes. It has also been used in prior studies of stair incidents (Templer, Mullet, Archea, & Margulis, 1978; Archea et al., 1979; Cohen, 2000), although earlier studies were limited due to the technological constraints and high costs of video recording at the time.

In store 1, stair use at the bottom portion of the first flight and at the top portion of the second flight was recorded on a Saturday and Sunday, both very busy times for the stores, between 12:00 and 15:00 on two separate weekends. The video recorder was positioned to capture stair users from head to foot. The observer sat with the recording device in a

seating area for customers within 20 feet of the stairway. Such areas located directly in front or to the side of stairways can facilitate unobtrusive observations of stair users in public settings. In store 2, the observer moved around the store with the recording device due to the lack of seating with clear views of the stairway and overcrowding at the stair landing which also served as an elevator landing. Today, overt recording in public places is generally acceptable due to the ubiquitous use of electronic devices with video capabilities.

Video data were transferred to a computer for analysis. Preliminary data provided strong evidence of unsafe stair use in both store locations, however, due to the poor quality of video in store 2, it was determined that the study would focus on the data for store 1 only. During coding and analysis of video data, stair incidents were recorded, extracted and time-stamped so that examples of stair use could be located easily for further analysis. This process increased the observer's familiarity with typical stair behavior and unusual stair events as well as the observer's ability to recognize precipitating factors for stair incidents, such as head movements. Video clips were reviewed by colleagues who concurred that a controlled comparison study would be more fruitful than a single case study to identify patterns of stair use that could be attributed to the unique design of the stairway in the Apple store.

3.3.3. Comparison Study

3.3.3.1. Procedure

The scope of the main study was limited to using two hours of qualitative observations and analyzing stair users in descent only, due to limitations of video angles that make it difficult to observe people ascending. For example, at points near the front and bottom of

stairs, it is not possible to clearly see the ascending user's head/eye movements since their backs are turned. Observations were also limited to the bottom two flights of stairs or the portion of the stair that was available from the observer's point of view. As with the previous example, the observer can only see the bottom portion of a flight that winds and not the top portion that turns out of view.

3.3.3.1.1. Comparison Site Selection

Another winding public stairway at a shopping mall in the Buffalo area was identified for the study. This stairway was constructed in a conventional manner and was used as the comparison site (see Figure 9).



Figure 9. Selected stairway sites for cross-site comparison of stair use: glass stairway at an Apple Retail Store (left) and a conventional stairway at a shopping mall (right).

Selection of the comparison site was based on the winding stair configuration, presence of views from the stairs, prominent location of the stairs, and high frequencies of use, which are conditions similar to those in the Apple store. Both stairways are open to the

surrounding but have different lengths and configurations. In the shopping mall, seven risers per flight and five flights of stairs rise clockwise in a wide quarter-turn (90 degrees). In comparison, the glass stairway has fifteen risers per flight and four flights that wrap around a cylindrical tube in the opposite direction (a full 360 degrees) (see Table 4). The shopping mall stairway is longer but each flight is nearly half the length of one flight in the Apple store and the radius of the turn is much larger, which reduces the difference in tread depth (running) across the length of the tread.

Table 4. Profile of stairway portions observed in an Apple Retail Store and a shopping mall.

	Glass Stairway (GS)	Conventional Stairway (CS)
Views from the stair	Yes	Yes
Contrast on tread edges	No	No
Tread depth (inner)	≤ 11 in (280 mm)	11 in (280 mm)
Tread depth (outer)	≤ 1'-8" (508 mm)	n/a
Riser height	≤ 6 in (152 mm)	≤ 6 in (152 mm)
Handrail width	1.5 in (38 mm)	1.5 in (38 mm)
Number of flight(s) observed	1	2
Location of observed flights	Bottom flight	First 2 bottom flights
Riser count (top flight)	n/a	7
Riser count (bottom flight)	15	7

3.3.3.1.2. Checklist Development

A checklist of behaviors that are indicators of problems using a stairway and possible reasons for those behaviors was developed to guide the observational studies. The checklist included information about demographics, key safety behaviors (tread gaze, diverted gaze, and handrail use), typical behaviors (talking, using electronic devices, and carrying things), and noticeable stair incidents (see Figure 10). Stair incidents included hesitation, slipping, and losing balance which, in this study, are considered "precursors of falls."

Variables	Stair users								
	1	2	3	4	5	6	7	8	9
Age									
Child (ages 1-14)									
Young Adult (ages 15-24)									
Middle-Aged Adult (ages 25-64)									
Older Adult (ages 65+)									
Gender									
Female									
Male									
Key Behaviors									
Frequent tread gaze (3 or more glances at the treads)									
Infrequent tread gaze (2 or less glances at the treads)									
Diverted gaze									
Handrail use									
Typical Behaviors									
Talking									
Using electronic devices									
Carrying things									
Noticeable incidents									
Hesitation									
Loss of balance									
Misstep									

Figure 10. Observation checklist.

Tread gaze, or observed glances at treads, is a key safety related behavior because visual scanning of treads is important for depth perception, foot placement (Archea et al., 1979; Miyasike-daSilva & McIlroy, 2012) and postural control (Hollands & Zietz, 2009; Den Otter, Hoogwerf, & Van Der Woude, 2011). Depending on how safe the stairway appears to the user, tread gaze occurs either frequently or infrequently and can be measured by the number of gazes per step, e.g. once every seven steps taken (Templer, 1992). Frequent tread gaze was measured when the user glanced at the treads three or more

times throughout an entire flight of stairs, and infrequent tread gaze was measured by glance frequencies of two or less times. Glances were measured each time the user's head turned downwards towards treads. For safe negotiation of stairways, one glance may be necessary at the beginning, middle, and end phases of stair walking, or the transitions and middle steps of a flight of stairs. Thus, three glances were used as a measure of safe attention to the stair climbing task.

Diverted gaze and handrail use were included because these variables could indicate several aspects of stair use including user comfort, distraction, and caution on the stair (Archea et al., 1979; Templer, 1992). The checklist was used to record the characteristics and behaviors of each individual stair user descending stairways for cross-tabulation.

3.3.3.1.3. Collection and recording of data

Shoppers ($N = 545$) were observed in the shopping mall on a Monday and Saturday. Observations were conducted during the late afternoon using the same procedure as study 1 (see section 3.3.3.1.). Video data were coded and analyzed using the checklist to record stair incidents. From study 1, two hours of the video data were randomly selected, and Apple customers ($N = 528$) were re-observed using the same method of evaluation.

3.4. Results

3.4.1. Exploratory Study

The exploratory study, which was conducted to better understand the types of incidents occurring on the glass stairway, revealed 110 abnormal stair events in six hours of observations. These included hesitations (disrupted gait), missteps, loss of balance,

collisions, and stumbling. No actual falls were observed. The result showed that there was one abnormal stair event every three minutes in the Apple store.

Thirty-six of these incidents were identified as high risks for falls due to clear missteps or disrupted gait patterns (see Table 5). Based on this data, one high risk incident could occur in the Apple store every ten minutes. Seventy-five percent (27) of these incidents occurred at the first four steps of the bottom or top of stair flights. Incidents occurred while the user's gaze was directed away from the stairs (53%) but also while the user's gaze was directed towards treads (47%).

Table 5. Results of the exploratory study with a 6 hour sample of stair use.

High risk incidents on the glass stairway	Frequency
Awkward foot placement	7
Catch toe or heel on nosing	6
Poor balance	6
Hesitation	5
Toe slides on nosing	4
Stumble	4
Overstep, misses tread	2
Collision	2

3.4.2. Comparison Study

The incidence of unsafe behavior as a percent of all stair descent on the glass stairway was 6.2% compared to 0.7% on the conventional stairway (see Table 6). There was one stair incident every 16 users in the Apple store and one stair incident every 136 users in the shopping mall. Eight times more people used the shopping mall stairway safely than the Apple store stairway.

Table 6. Cross-site comparison of the incidence of hesitation, misstep, and loss of balance during descent on the glass stairway and the conventional stairway.

High risk incidents	Glass Stairway (GS) (<i>N</i> = 528)	Conventional Stairway (CS) (<i>N</i> = 545)
Hesitation	4.16% (22)	0.18% (1)
Misstep	0.37% (2)	0.18% (1)
Loss of balance	1.70% (9)	0.36% (2)
Total	6.25% (33)	0.73% (4)

Hesitation or sudden disruption in walking movement occurred at an incidence of 4.1% in the Apple store compared to 0.1% in the shopping mall. Loss of balance was the second most frequent unsafe behavior observed in the Apple store (1.7%) while it occurred in the shopping mall at less than half that rate (0.3%). The rate of missteps in the Apple store was twice the rate of those in the other building.

More stair users glanced down at the winding treads made of glass than the winding treads made of conventional material (GS: 87% vs. CS: 60%) (see Figure 11). In addition, it was noted that frequent tread gaze was involved in 67% of the stair incidents in the glass stairway compared to 25% of the incidents that occurred in the conventional stairway; in the conventional stairway, incidents were more associated with infrequent tread gaze, or glances at treads (75%).

Fewer stair users diverted their gaze on the glass stairway (GS: 55% vs. CS: 67%) which may explain the higher rates for glances at the glass treads (see Figure 11). When returning attention to the stairway, users may have a tendency to re-orient themselves by glancing at the stairs. It was noted that diverted gaze was involved in 72% or 24 of the

stair incidents in the glass stairway ($N = 33$), and it was involved in every stair incident in the conventional stairway ($N = 4$).

Handrail use was generally infrequent in both stairways, but higher in the glass stairway (GS: 32% vs. CS: 25%) (see Figure 11). This supports research findings that handrail use is often minimal (Templer, 1992; Cohen & Cohen, 2001). Finally, it was noted that 1.5% (8) of stair users in the glass stairway descended to their left side where the treads were wider. This was clearly a cautionary behavior. The study did not find any significant patterns in typical user behaviors (talking, using electronic devices, and carrying things).

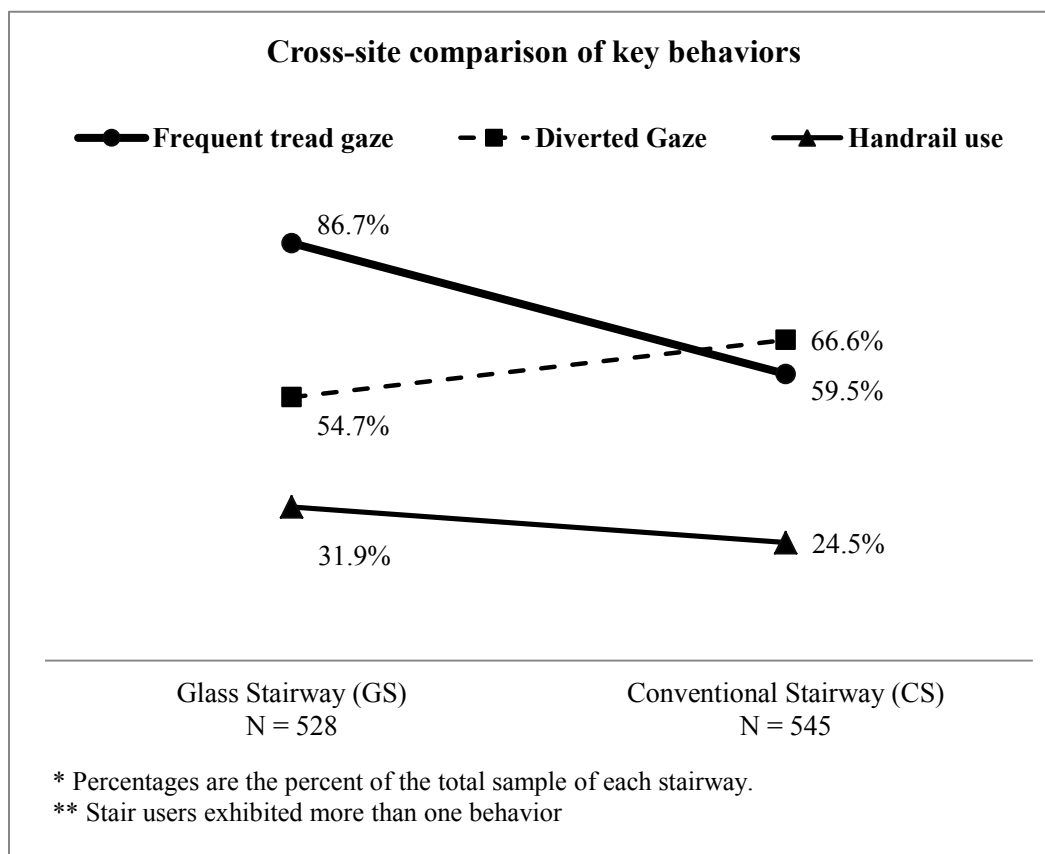


Figure 11. Cross-site comparison of key behaviors.

3.5. Discussion

The study found that the incidence rate for hesitation, misstep, and loss of balance was significantly higher in the glass stairway compared to the conventional stairway which confirmed the first hypothesis. This suggests that people experience disruptions in gait and lose their balance more frequently in the Apple store than in conventional buildings. The results suggest that the use of glass stair treads may be a contributing factor.

3.5.1. Visibility of Glass Stair Treads

The fact that the glass stairway had the highest incidence of gait errors despite also having higher rates of tread gaze suggested that many people in the Apple store were not able to accurately perceive the stairs even while looking at the treads frequently, thus, visibility of treads in either foveal or peripheral vision may be difficult. Frequent tread gaze was more associated with stair incidents on the glass stairway (66%) than the conventional stairway (25%) where incidents were more associated with fewer glances at the treads as might be expected. For example, in a video clip, a man approaching for stair ascent is gazing at the glass treads when his leading foot swings forward and hits the edge of the first step. The professional literature acknowledges the benefits of using visual contrast on tread edges to increase visibility of steps (Archea et al., 1979; Templer, 1992) however research is needed to demonstrate the evidence of its effectiveness for glass treads in particular. Further, research is needed to determine whether standards for the use of glass flooring for stairways should enforce high contrast edges, especially in public places where a large and diverse number of people are expected to use the stair.

3.5.2. Visual Distractions in the Apple Retail Store

Although shifting of gaze between the stairs and surrounding occurred less in the Apple store, the total number of incidents that involved the user looking away from the stairs either before or at the time of the incident was significantly higher in the Apple store ($n = 24$) than the conventional building ($n = 4$). This finding suggests that being distracted by surrounding views is more likely in the Apple store, which supports the second hypothesis. In a video clip, a man ascending the bottom of the stairs and looking to his right towards the interior of the Apple store understeps the fourth tread and nearly falls. More video analyses revealed that the first four steps of the bottom or top of each flight were prone to missteps due to interior views of the store causing people to divert their gaze away from the stairs. The areas along the stair's curvature where the steps gradually turned toward the same views as described above were prone to the effects as well, which is consistent with research on stair incidents occurring on steps that expose stair users to different views (Templer, 1992). More attention is needed on how to design winding stairways in relationship to attractive features of the surrounding environment. Furthermore, since distractions are likely to affect the user's perception of treads as they return their attention to the task of traversing stairs, research should focus on how to make the stair edge visible to an inattentive user's peripheral vision (Archea et al., 1979; Sloan, 2011), especially with materials like glass where the edge is difficult to perceive, and how to encourage use of handrails to maintain balance if a misstep occurs (Maki et al., 2011).

3.5.3. The Direction of Stair Curvature

Although the stairways differed in shape and direction of curvature, making it difficult to present direct comparisons, it is not inconceivable that the direction of stair curvature

played a role in stair incidents. The study found that some people exhibited behaviors of fear or confusion towards using the glass stairway for descent while such behaviors were rarely observed in the conventional stairway. For example, in a video clip, an elderly woman slowly descending to her left with a cautious gait and holding onto the handrail is repeatedly forced to let go of the handrail and move aside for ascending traffic on the same side of the stair. This example suggested that for some people, the preferred way of using the stairway rising in the anticlockwise direction was to use the left side for descent, even though this path created conflict with others who were ascending while staying to their right, as is the convention in the U.S. Alternatively, a stairway rising in the clockwise direction would make the right-side descending path more acceptable to users. Although this strategy places ascending users on narrower treads, research has indicated that there may be a greater need to design for safer stair descent since it is the more dangerous task (Templer, 1992). Studies comparing the winding direction would be useful to clarify the effect of stair curvature on incidents.

3.5.4. Gait Characteristics and Strategies in the Apple Retail Store

People showed a higher frequency of safety behaviors on the glass stairway (i.e. tread gaze, handrail use, less diverted gaze, and use of the left-side descending path) which suggested that people perceived the glass stairway as more dangerous than the conventional stairway. As a result of this perception, people may step on the treads more carefully or limit their movement as a strategy for postural stability such that they are depending less on the quality of the walking surface and more on their own ability to traverse the stairs safely. Although previous studies suggest that slower walking speed and shorter stride length should lower the amount of friction needed on floors to prevent slipping, other studies have found that it is also possible for people with uncertain walking styles to have a higher risk of falls (Christina & Cavanagh, 2002), particularly

among people with physical or cognitive loss who may have experienced a loss of skills to avoid slips and falls (Lockhart et al., 2009). Longer strides, which are commonly associated with greater frictional demand, were observed when people descended along the wider end of the treads as well as when people veered off the path of travel while descending (i.e. walking in a diagonal manner across the stairs) as a result of looking away from the stairs.

Other gait issues were observed that could be attributed to the design of the Apple store stairway. In a video clip, an elderly man is descending, looking to his left, and holding onto the handrail. As he releases grip of the handrail and steps down onto the landing, he grimaces in pain. A still image of that scene revealed that he had overextended his gait slightly which suggested that the landing foot and leg were unstable and could not support the entire weight of his shifting body. One possible reason for this could be that the man miscalculated foot placement during walking movements in the direction ahead of the stair while his attention was diverted to his left in a different direction. Such gait problems may be related to individual health conditions and perceptual abilities, but the study suggested that the distractions causing the user to look away from the stairs at critical walking points is an exacerbating factor. In addition to the variety in gait styles and strategies, footwear may contribute to slipping on the glass treads. In a video clip, a woman wearing boots and holding the handrail is gazing downwards as she lowers her left foot onto the first tread. Her landing foot shifts inwards and she stumbles forward towards the handrail. If this incident was caused in part by little low friction between the boots and tread, there may be an issue with the glass surface involving slip resistance for a wide range of shoe materials. These findings suggested that walking on glass treads in a winding configuration may be more complex than is currently understood.

3.5.5. The Use of Glass As a Flooring Material

The present study led us to question how architects choose building materials for stairway design and, in particular, what factors are considered when selecting glass as a flooring material. Clearly glass is an unusual flooring choice for stairway design in comparison to materials such as concrete, wood, carpet and stone which are more commonly associated with our perceptions of safe walking surfaces. The tactile or visual quality of the glass material may actually transmit cues that some users perceive as evidence of danger. The effects could cause hesitation to using stairways in buildings, as suggested by this study, and even avoidance.

Walking surfaces should be "stable, firm, and slip-resistant" (U.S. Access Board, 2002) and without barriers to access and equal participation. The capability of flooring products to resist sliding motions of the feet is indicated by the measurement of the static and/or dynamic coefficient of friction (COF) between the shoe and floor such that a higher COF value minimizes the risk of slipping. In 2009, the American National Standards Institute (ANSI) and the National Floor Safety Institute (NFSI) set the first national standard for floor safety that quantified a wet static COF of 0.6 and three risk categories (Kendzior, 2011). But prior to this standard, and for decades, the accepted industry practice had been dry testing for a static COF measurement of 0.5. This has also been recommended for glass walkways by the American Society for Testing and Materials (ASTM) (Glass Magazine, 2012). These standards are not mandated unless adopted by a government, agency or client (ANSI, n.d.), although their adoption could provide a "safe haven" for material manufacturers and architects by protecting them from liability claims.

Since there has not been a universally agreed-upon criteria for what type of friction (i.e. static or dynamic) and what specific COF values are needed to determine slip resistance,

U.S. building material industries have been measuring and reporting the slip resistance of their products in different ways based on different measurement devices. The reliability of these devices is questionable. For example, the Horizontal Dynamometer Pull-meter is an ASTM test method that requires a person to pull on the weight of an object sitting on a surface until the weight moves across that surface. But the force and speed of pulling by the operator may produce different COF results. This method measures only the static COF under dry and wet conditions in a laboratory setting (ASTM International, n.d.). The ANSI/NFSI approved BOT-3000, on the other hand, is an automated tribometer that measures both static and dynamic COF, wet and dry, in either the laboratory or field (Safety Direct America, n.d.). Studies suggest that different tribometers produce different test results for the same product and that test results often do not reflect how the flooring surface is actually used in the real world (Kim, 2012).

A scan of online product catalogs will show that glass flooring material is often associated with slip resistance either with a "slip resistant" label or with COF values indicating that the material had been tested. A description of how the glass material was actually tested and using what testing device is sometimes excluded, making it difficult for the architect to interpret the data, compare one glass product with another, and make informed decisions. For example, a glass product labeled as slip resistant may be unsafe for some users or, even worse, under some conditions of use but not others, e.g. when wet as opposed to dry. Thus, accepting current slip resistant information provided by glass manufacturers as proof of slip resistance may be difficult.

In light of the disparities in recommendations for slip resistance and given the early stages of development in floor safety standards, there is a need to assess existing walkways and stairways that may be adhering to outdated test results. Moving forward in

the "new era of increased walkway safety and liability" (Troyer, 2012), architects will need to make more conscious decisions about using glass flooring materials in public stairway projects by understanding the issues related to the stair user's behaviors as well as the testing method and testing device that was used in evaluating the glass product in relationship to current slip resistance standards. Stairways are important parts of architectural design and have increased liability risks due to their inherent danger. A fall on a glass stairway may be attributed to the flooring material in which case the architect, the tread manufacturer, the contractor, or the building owner may be held responsible.

3.5.6. Limitations and Future Work

The study compared stairways with different characteristics using two hours of observations. Longer or more frequent observation periods could produce different results, although the short observation period did result in reasonable sample sizes. Studies of stairways that are more comparable in design would provide more direct comparisons of targeted stair features. In addition, a larger sample would provide more data on the impact of those features on different age groups; this study did not have enough data for each age group to analyze this relationship.

Another limitation of the study was the video angles used in the observations. The study method did not allow the observer to see some portions of stairways and observe stair users continuously for the full length of each flight, thus, the study is probably underreporting the frequency of stair incidents. Simultaneous observations at the bottom and top of winding stairways would provide complete descriptions of stair ascent and descent. Clearly this presents more technological challenges and would also be more obtrusive.

Although the study was based on naturalistic observations rather than automated data collection of user behavior such as the use of an eye-tracking device or motion analysis, the video recording method allowed the observer to track head movements that were purposefully aimed downwards, which is strongly suggestive of gaze aimed at the treads. This study demonstrated that the use of video recording for observations of stair use is an inexpensive and easy to implement method for assessing stairway design features that are being used in public places without appropriate research evidence. Further studies using this empirical method would add to our knowledge of contemporary stairway designs and contribute to improving the usability and safety of stairways for diverse users. Furthermore, laboratory studies would provide reliable information about the issues in growing trends in stairway design before they are used widely. Contemporary practices, such as open risers, interactive sound and light, and embedded LEDs clearly require similar research attention.

3.6. Conclusion

Stair safety can be improved by increasing awareness and understanding of how and why trips, slips and balance problems occur. This study assessed a current stairway design practice, the use of glass as a tread material, by observing stair users and comparing the incidence of unsafe stair use on an innovative glass stairway in an Apple Retail Store with a stairway of similar configuration made of conventional materials in another retail building. The study identified differences in the behavior of stair users between the two stairways. The results indicated that walking on glass treads may be more dangerous than walking on conventional treads due to reduced visibility of glass edges or reduced friction between shoes and treads. This study provides new insight into the role of glass stair treads in stair safety, however, further studies of actual falls or incidents on other

glass stairways are needed to confirm these results. As it stands, there is little evidence supporting glass as a flooring material in public places when there are factors to consider such as the absence of a universal test method to ensure equality of walkway safety and walking opportunities.

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Chapter 4

4. The Effects of Interactive Sound on Stair User Behavior and Safety

4.1. Abstract

The social context for stairway design in multi-story buildings is changing. At one time, stairways were viewed primarily as a means of egress in an emergency, and elevators or escalators were the primary method of vertical circulation with the exception of monumental “feature” stairways. Today, the emphasis is changing to promote the use of stairways in buildings as opposed to use of elevators due to the health benefits of stair climbing. This is providing an opportunity for architects and building owners to experiment with innovative designs. One interesting innovation is the “interactive stairway.” Little is known about the impact of these interventions on the rate of stair accidents. The purpose of this study was to assess the safety of interactive stairway designs by observing the user's behavior and to identify concerns for this trend. A checklist for recording observations of stair use was developed. Observations of stair use were conducted in two museum buildings with interactive stairways and in one university building with a conventional stairway. The incidence of unsafe stair use and key behaviors (tread gaze, diverted gaze, and handrail use) on the interactive stairways (CM and SM) and the conventional stairway (SU) were documented and compared. Incident rates were similar across the stairways (CM: 2.2%, SM: 2.2%, SU: 2.6%). On the interactive stairways, more stair users glanced down at the treads (CM: 90%, SM: 81% vs. SU: 53%); fewer stair users diverted their gaze away from the stairs (CM: 22%, SM: 32% vs. SU: 66%); and handrail use was higher (CM: 40%, SM: 33% vs. SU: 28%).

Although stair users displayed more compensatory behavior, interactive stairways can be as safe as any other stairway due to unexpected stimuli.

Keywords. Stair safety, stairway, interactive stairway, interactive sound, sound environment, universal design, assessment, observational studies, gaze behavior.

4.2. Introduction

Stairways are one of the most dangerous parts of the built environment. In a flight of stairs, each step is a physical obstacle that can interfere with foot clearance and cause a person to lose balance and fall. The risk is exacerbated by flaws in the design and construction of stairways (Archea et al., 1979; Templer, 1992), such as non-uniformity of risers and treads, which often become the subject of litigation (Cohen, LaRue, & Cohen, 2009). To make matters even worse, stairways are often not perceived by users as being dangerous unless stair defects are visibly noticeable (Pauls, 2013a). In the United States, stairways are a leading site of fall-related injuries, accounting for 1,900 deaths (NSC, 2011) and 1.3 million hospitalizations per year (Pauls, 2011). A stair-related injury requiring hospital treatment is likely for every 1,766,000 flights of stairs climbed (Pauls, 2013a). The 2013 annual cost to society for these injuries is 100 billion dollars in medical and litigation expenses which far exceeds the cost of stairway construction (Pauls, 2013b). The increasing burden of stairway falls has drawn attention to research needs for assessing current practices and knowledge gaps for design of stairways.

Since the advent of elevators, stairways are hidden in multi-story buildings and have less than desirable qualities, often as a result of being overlooked in the design process. In recent years, however, there has been growing interest in the role that stairways may play

in reducing obesity rates in the U.S. (Cohen, 2013). In 2013, New York City Mayor Michael Bloomberg issued an executive order requiring that all new and renovated City buildings meet active design strategies (City of New York, 2013). It is now recommended that architects design highly visible, easy to access, and attractive stairways to encourage use (City of New York, 2010). “Interactive stairways” are one thread of activity related to this new emphasis in design practice. While there has been a great deal of interest in encouraging stair use on both architectural and policy levels, much less emphasis has been placed on stair safety. For example, several studies have examined the effectiveness of signs, artwork, music, and interactive features to promote the use of stairs when elevators or escalators were present (Boutelle et al., 2001; Lee et al., 2012; Swenson & Siegel, 2013), but, no studies have attempted to assess the impact of these interventions on the rate of stair incidents. These studies would be warranted simply because a higher frequency of stair use, for any reason, increases the exposure to risks of tripping, slipping and falling. But, in interactive stairways specifically, the interventions have the potential to have an unsafe impact by causing distraction from the stair climbing task and altering gait while traversing the stairway.

Compared with other interventions, interactive features have shown a significantly higher impact on stair use and thus greater promise for stairway design as an intervention for promoting health and fitness (Swenson & Siegel, 2013). This study considers interactive features such as sound effects, embedded LED, and other technologies that affect the entire stairway as opposed to individual elements such as interactive art hanging along stairway walls or attempts to turn the entire stairway into an artwork with paint, sculpture or stair configuration. Interactive stairways can change the purpose or the “imageability” of stairways in buildings (Nicoll, 2007 cited in Swenson & Siegel, 2013) by allowing users to engage in stair climbing tasks while feeling as though they are having an

influence on the built environment (Swenson & Siegel, 2013). Moreover, these features are able to detect movement on stairs through sensor technology which allow users to sense their own movements as feedback is triggered. Perhaps the best known example of this type of stairway was the "Piano Stairs" at the Odenplan subway station in Stockholm, which was part of Volkswagen's "The Fun Theory" campaign in 2009. This subway stairway, located next to an escalator, was modified to look like a piano keyboard and play musical notes when users ascended and descended the steps. The study, aimed at changing sedentary behavior by making the stairway fun to use, reported a 66% increase in stair use over escalator use (The Fun Theory, 2009).

This study investigated the effects of interactive stairway features on user behavior and safety by comparing behavior on these stairways with a conventional stairway design. In the U.S., interactive stairways are gaining popularity, especially in museums as technology exhibits, which present some research opportunities to learn more about their impact. There are several potential safety problems with interactive stairways. First, they provide incentive for repeated use of stairways, increasing the exposure to risks. Second, since stair climbing is largely affected by visual attention (Archea et al., 1979; Holland & Zietz, 2009; Miyasike-daSilva & McIlroy, 2012), it would be useful to understand the relationship between gaze behavior and stair climbing when engaged with interactivity. Third, stair users are likely to exercise more caution in the presence of known distractions and design interventions (Templer, 1992), thus, it could be that these interventions increase attention to the stairway use task, mitigating any negative impact on safety. Lastly, interactive stairways motivate people to use the stairs in unconventional ways. For example, sounds effects that are triggered by movements often cause people to run, jump, skip, and even dance on the steps. These types of movements may require special

consideration for safety features such as handrails, slip resistant treads, and visibility of stair tread edges.

4.3. Methods

4.3.1. Hypotheses

The following hypotheses guided the research:

- **H1:** Interactive stairways attract the user's gaze to the stairway itself.
- **H2:** There will be less diverted gaze to the surroundings.
- **H3:** There will be more handrail use on interactive stairways.

4.3.2. Protocol

The University Institutional Review Board determined that the research did not meet the definition of human subjects. We did not gain any personal information about people through intervention or interaction therefore no IRB approval was needed for the project.

4.3.3. Feasibility Test

Video recording was chosen as the study method as recordings could be replayed repeatedly for analysis purposes. It has also been used in prior studies incidents (Templer, Mullet, Archea, & Margulis, 1978; Archea et al., 1979; Cohen, 2000), although earlier studies were limited due to the technological constraints and high costs of video recording at the time. A pilot study was conducted at a selected site to determine the feasibility of using this study method to collect data (see Chapter 3). The study consisted of a successful data collection and analysis phase, during which the observer became familiar with recognizing stair behaviors and precipitating factors for stair incidents.

4.3.4. Site Selection

Two interactive stairways, one at the Children's Museum of Pittsburgh (CM) and one at the Science Museum in Boston (SM), were selected as the sites for observations (see Figure 12). One other public stairway at the University at Buffalo Student Union (SU) was identified as the comparison site.

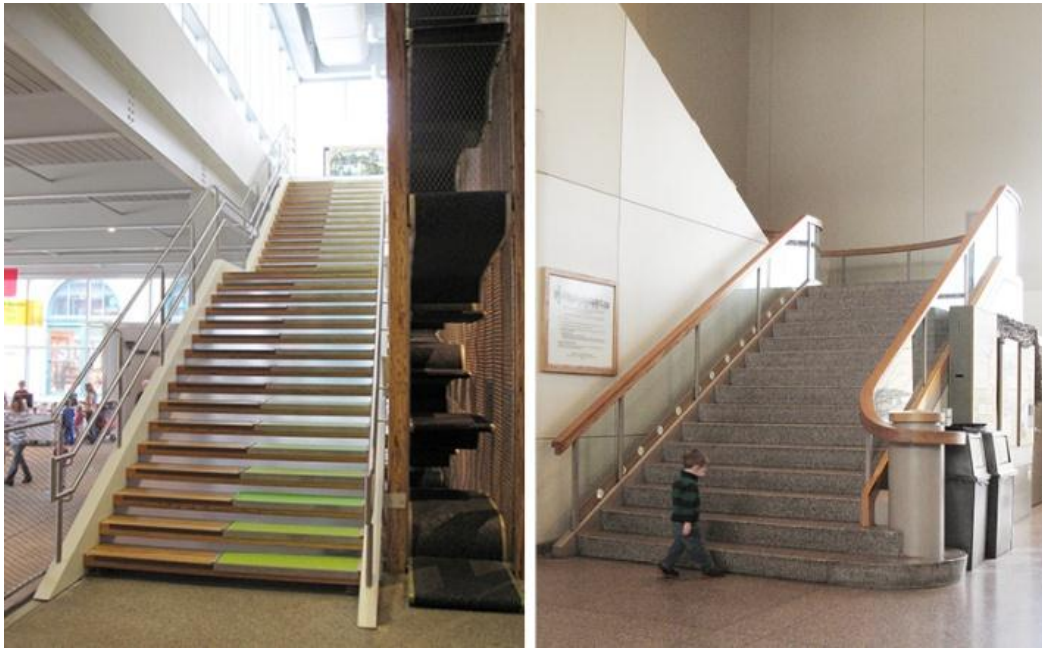


Figure 12. Interactive stairways at a Children's Museum (left) and a Science Museum (right).

The Children's Museum stairway (CM) was equipped with sensor stair pads made of vinyl composition tile in green color that activate sounds of children's voices from speakers when pressure is applied to the surface. The stair pad system was installed only on one side of the stairway, for the right-side ascending path, and does not stretch across the entire stair width. This results in an uneven tread surface and a trip hazard along the middle of the stairway. This stairway has sixteen risers per flight, two flights of stairs, and handrails for both adults and children in a relatively enclosed space that obscures surrounding views (see Table 7).

Table 7. Profile of the stairways in the museum buildings and the university building.

	Children's Museum (CM)	Science Museum (SM)	Student Union (SU)
Views from the stair	No	Yes	Yes
Tread edge contrast	Only on one side	No	Yes
Tread depth	12 in (305 mm)	≥ 11 in (279 mm)	11 in (279 mm)
Riser height	5.8 in (149 mm)	6.7 in (171 mm)	8 in (203 mm)
Riser count (top)	16	n/a	10
Riser count (bottom)	16	15	13
Handrail width	1.5 in (38 mm)	3.5 in (89 mm)	2.25 in (57 mm)

The Science Museum stairway (SM) uses invisible light beams to detect stair users and activate harmonic sounds. Detection occurs when users cross light beams between photoelectric sensors and reflectors. Sounds change in pitch and melody based on the user's patterns of ascending and descending. This stairway has fifteen risers per flight, ungraspable handrails, and provides clear views to the surrounding space (see Table 7).

The two interactive stairways are different from one another. The stairway in the Children's Museum (CM) is enclosed, longer in length, and narrower, whereas in the Science Museum (SM), it is open to the surrounding and wider which allows more people to use the stairs simultaneously. The comparison site has views from the stairs and location prominence, which are conditions similar to those in the Science Museum. The Children's Museum share some but not all of these conditions.

4.3.5. Checklist Development

An observation checklist was developed to record each stair user descending stairways for cross-tabulation. The checklist included information about demographics, key safety behaviors (tread gaze, diverted gaze, and handrail use), typical behaviors (talking, using

	Stair users								
Variables	1	2	3	4	5	6	7	8	9
Age									
Child (ages 1-14)									
Young Adult (ages 15-24)									
Middle-Aged Adult (ages 25-64)									
Older Adult (ages 65+)									
Gender									
Female									
Male									
Key Behaviors									
Frequent tread gaze (3 or more glances at the treads)									
Infrequent tread gaze (2 or less glances at the treads)									
Diverted gaze									
Handrail use									
Typical Behaviors									
Talking									
Using electronic devices									
Carrying things									
Noticeable incidents									
Hesitation									
Loss of balance									
Misstep									

Figure 13. Observation Checklist

electronic devices, and carrying things), and noticeable stair incidents (see Figure 13). Stair incidents included hesitation, slipping and losing balance which, in this study, are considered "precursors of falls."

Tread gaze, or observed glances at treads, is a key safety related behavior because visual scanning of treads is important for depth perception, foot placement (Archea et al., 1979; Miyasike-daSilva & McIlroy, 2012) and postural control (Hollands & Zietz, 2009; Den Otter, Hoogwerf, & Van Der Woude, 2011). Depending on how safe the stairway appears to the user, tread gaze occurs either frequently or infrequently and can be measured by

the number of gazes per step, e.g. once every seven steps taken (Templer, 1992). Frequent tread gaze was measured when the user glanced at the treads three or more times throughout an entire flight of stairs, and infrequent tread gaze was measured by glance frequencies of two or less times. Glances were measured each time the user's head turned downwards towards treads. For safe negotiation of stairways, one glance may be necessary at the beginning, middle, and end phases of stair walking, or the transitions and middle steps of a flight of stairs. Thus, three glances were used as a measure of safe attention to the stair climbing task.

Diverted gaze and handrail use were included because these variables could indicate several aspects of stair use including user comfort, distraction, and caution on the stair (Archea et al., 1979; Templer, 1992). The checklist was used to record the characteristics and behaviors of each individual stair user descending stairways for cross-tabulation.

4.3.6. Collection and Recording of Data

The scope of the study was limited to using two hours of qualitative observations and analyzing users in descent only, due to limitations of video angles that make it difficult to observe people ascending. For example, at points near the front and bottom of stairs, it is not possible to clearly see the ascending user's head/eye movements since their backs are turned.

Observations were conducted by the author using a video recorder at the Children's Museum (CM) on a Friday and at the Science Museum (SM) on a Sunday between 12:00 and 14:00. Observations were collected at the comparison sites (SU) on a Tuesday and Thursday in the late afternoon. At each site, the video recorder was positioned to capture stair users from head to foot within 20 feet of the stairway. The observer either sat with

the recording device in a seating area or sat in a seating area a few feet away from the video recorder. Such areas located directly in front or to the side of stairs can facilitate unobtrusive observations of stair users in public settings.

Video data were transferred to a computer for observation and analysis. Stair users were observed for two hours, coded, and analyzed in descent. This process increased the observer's familiarity with typical stair behavior and unusual stair events as well as the observer's ability to recognize precipitating factors for stair incidents, such as head movements. Stair incidents were recorded on the checklist, extracted from the video data, and time-stamped so that examples of stair use could be located easily for further analysis.

4.4. Results

A total of 92 stair users in the Children's Museum (CM), 502 stair users in the Science Museum (SM), and 453 stair users in the Student Union (SU) were observed. The incidence of unsafe behavior as a percent of all stair descent was similar across all three samples (CM: 2.2%, SM: 2.2%, SU: 2.6%) (see Table 8).

Table 8. Cross-site comparison of the incidence of hesitation, misstep, and loss of balance during descent on the interactive stairways and the conventional stairway.

	Children's Museum (CM) (N = 92)	Science Museum (SM) (N = 502)	Student Union (SU) (N = 453)
Hesitation	1.08% (1)	0.39% (2)	1.54% (7)
Misstep	0.0% (0)	0.39% (2)	0.22% (1)
Loss of balance	1.08% (1)	1.19% (6)	0.88% (4)
Fall	0.0% (0)	0.19% (1)	0.0% (0)
Total	2.17% (2)	2.19% (11)	2.64% (12)

In the Children's Museum, 4% (4) of the users repeatedly used the stairway. Nearly 23% (21) of the users walked on the sensor stair pads along their left-side descending path, which is the "wrong" side of the stairway. One stair incident (50%) occurred as a result of intentionally using the interactive feature. In the Science Museum, 17% (86) of the users repeatedly used the stairway. Three of the stair incidents (27%) occurred as a result.

Hesitation or sudden disruption in walking movements occurred at a slightly lower rate in the Science Museum (SM: 0.4% vs. CM: 1.1%, SU: 1.5%) (see Table 8). Loss of balance rates were virtually the same across the buildings (CM: 1.1%, SM: 1.2%, SU: 0.8%). Misstep rates were higher in the Science Museum (0.4%) compared to 0.2% in the Student Union; no missteps occurred in the Children's Museum. One fall was observed in the Science Museum (0.2%) as a result of a child jumping on the stairs.

On the interactive stairways, more stair users glanced down at the interactive steps than the conventional steps (CM: 90%, SM: 81% vs. SU: 53%) (see Figure 14). It was noted that frequent tread gaze was involved in most of the stair incidents in the museum buildings (CM: 100% or $n = 2$, SM: 82% or $n = 9$) compared to 42% (5) of the incidents that occurred in the conventional stairway; in the Student Union, incidents were more associated with infrequent tread gaze (58%).

Fewer stair users diverted their gaze away from the stairs (CM: 22%, SM: 32% vs. SU: 66%) (see Figure 14). When returning attention to the stairway, users may have a tendency to re-orient themselves by glancing at the stairs. It was noted that diverted gaze was involved in fewer stair incidents in the museum buildings (CM: 50% or $n = 1$, SM: 36% or $n = 4$), and it was involved in almost every stair incident in the Student Union (92% or $n = 11$).

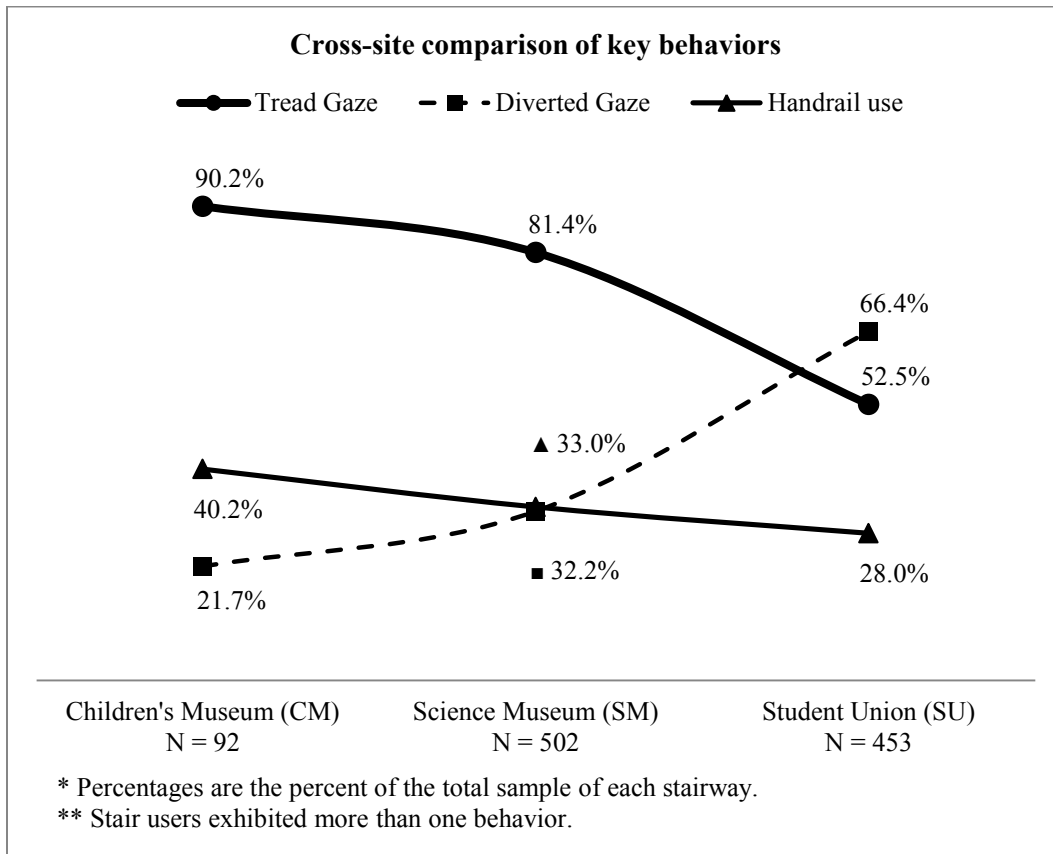


Figure 14. Cross-site comparison of key behaviors.

Handrail use was highest in the Children's Museum and lowest in the Student Union (CM: 40% vs. SM: 33%, SU: 28%) (see Figure 14). The rate of handrail use in the conventional stairway supports research findings that handrail use is often minimal (Templer, 1992; Cohen & Cohen, 2001). The results support the hypothesis that stair users would display more compensatory behavior by looking at the tread more and less at the surrounding environment, and by using the handrail more. The study did not find any significant patterns among age groups as well as in typical user behaviors (talking, using electronic devices, and carrying things).

4.5. Discussion

4.5.1. Interactivity in Stair Performance

Although more stair users in the museum buildings displayed behaviors associated with safety to compensate for the changes in how stairways are traditionally used, the study found that the incidence rate for hesitation, misstep, and loss of balance were similar across the stairways. This suggests that interactive stairways can be as safe as any other stairway. Furthermore, the results support the notion that in an otherwise conventional stairway, stair users tend to focus their visual attention on the surrounding environment where views are present, rather than their stepping locations, and use less of the handrail, which are behaviors that increase the risk for slipping, tripping and falling (Archea et al., 1979; Templer, 1992). Given that the incidence of unsafe stair use was similar across the stairway designs and that there were higher rates of compensatory behaviors in the interactive stairways, it would be fair to say that the real dangerous stairways are the ones that are not perceived as dangerous. When a hazardous condition is not perceived, users do not take compensatory action.

In terms of visual attention on the interactive stairways, tread gaze occurred more frequently and was involved in most of the stair incidents. While research suggests that stair users are likely to exercise more caution in the presence of known distractions and design interventions, the results suggested that unexpected or novel events can capture the user's attention in an involuntary way to focus attention to a potential danger but, at the same time, distracting attention away from a task at hand. Thus, interactive features could create distraction or user engagement, depending on the nature of the stimuli. For example, random and novel noises could be more of a distraction but music more of a

focusing sound. It would also be useful to know how distractions created by interactions affect gait on stairs and whether some groups of users may be affected more than others.

Although the study found greater incidences of tread gaze and handrail use on the interactive stairways compared to the conventional stairway, there were no significant differences in altered gait, suggesting that these behaviors compensated for the distractions that interaction may cause. Among experts, prevailing wisdom is that the most dangerous risks are those that are not perceivable. This opinion seems to be confirmed by this study. But, at this point there is not enough data to justify the conclusion that interactivity leads to safer stairways. In Chapter 3, the findings suggested that people may have difficulty perceiving the risks of stairways even though they should be obvious. The novelty of interactivity could lead to increased vigilance and handrail use initially but may revert to conventional practice as they become accustomed to the design.

4.5.2. The Use of Interactive Stairways as Technology and Art Exhibits

The results of the study demonstrated that the interactive stairway features contributed to unsafe stair use behavior, therefore as the trend toward deployment of interactive stairways increases as a means to enhance the visitor's experience, it is important to learn more about how interactive design strategies actually affect stair safety behavior especially when the proper precautions, like provision of suitable handrails, are not taken. For example, in the Children's Museum, a stair incident had occurred as a result of intentionally walking on the "wrong" side of the stairway in order to interact with the stairway. In the Science Museum, 27% of the stair incidents had occurred as a result of repeated use of the interactive stairway, especially by children. It is not surprising that interactive elements enticed a group of children into using the stairways. Designers who

are exploring digital technologies to enhance the stair climbing experience should take notice because this puts children at greater risk of accidents. For example, when retrofitting existing stairways to interactive features, handrails should be provided to compensate for unconventional stair behavior. The Science Museum currently has ungraspable handrails that are also unreachable to small children.

When incorporating interactive technology in stairway design or as exhibits on stairways, it is important that the technology is installed so that it does not create potential unsafe conditions. For example, in the Children's Museum, perhaps it would be better to use pressure switches under pads across the entire stairway width and not only half of the stairway as this causes stair users descending to intentionally walk on the wrong side of the stair and conflict with others who are ascending while staying to their right. Clearly, motion sensors, which do not directly impact gait, are less intrusive than pads added to the treads. Understanding and applying interactive art technology requires more than just designing attractive stair features. Designers and creative artists need to use interactive design in a responsible and informed manner. Interactive stairways can indeed be more inclusive and engaging environments. Although the study did not include these results, the observations revealed repeated use among all age groups, demonstrating their appeal. Perhaps these installations can lead to improved stair safety. An increased public awareness is also necessary to reduce accidents. For example, adults should caution children when using interactive stairways or restrain children from using interactive stairways when safety hazards are present.

It should be noted that there are interactive stairway designs that are much more dangerous than those studied. For example, LED color displays (see Figure 15) and, at the Albright-Knox Art Gallery in Buffalo, NY, a stairway was turned into an art piece by

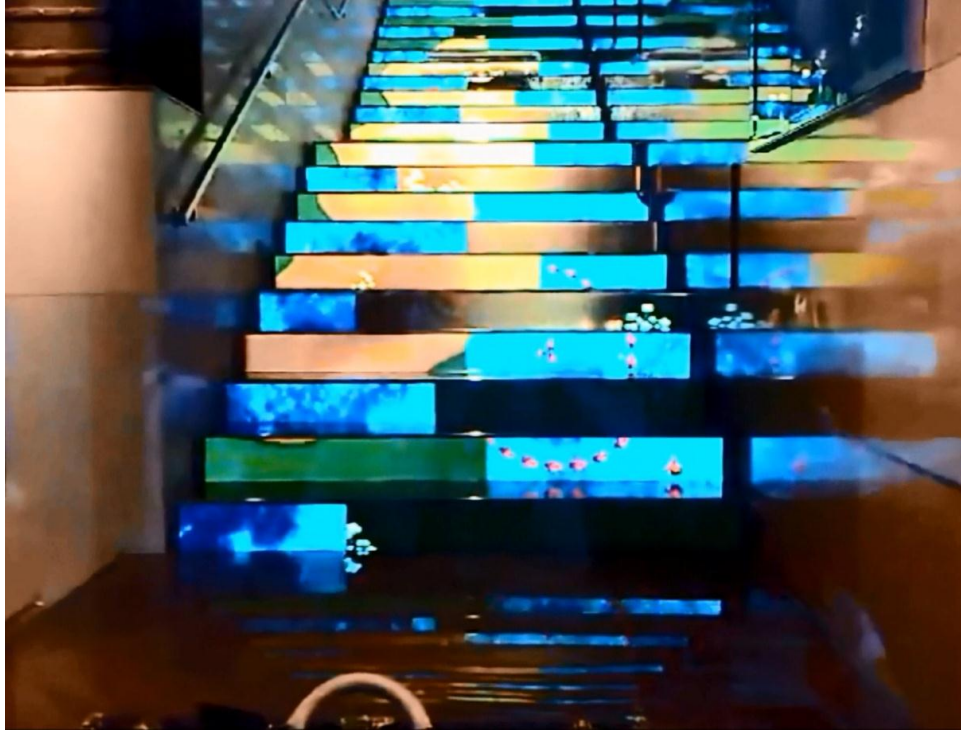


Figure 15. A stairway with LED color displays on stair risers (Source: YouTube user heinv, retrieved from [youtube.com/watch?v=uGEGyaxV9SU](https://www.youtube.com/watch?v=uGEGyaxV9SU))



Figure 16. A stairway with confusing tread pattern at the Albright-Knox Art Gallery (Source: M. Frederick)

painting it with a striped design that creates optic effects in the manner of Op Art, making it literally impossible to see the edges of the treads (see Figure 16). Additional research in this area could be very beneficial to identify what is dangerous and what is not, but education for museum administrators is also needed to acquaint them with the potential hazards and how to suitably protect people from exposure to risk, e.g. use of signs, barriers and do's and don'ts.

4.5.3. Limitations and Future Work

The study compared stairways with different characteristics using two hours of observations. Longer or more frequent observation periods could produce different results, although the short observation period did result in reasonable sample sizes. Studies of stairways that are more comparable in design would provide more direct comparisons of targeted stair features. In addition, a larger sample would provide more data on the impact of those features on different age groups; this study did not have enough data for each age group to analyze this relationship.

Although the study was based on naturalistic observations rather than automated data collection of user behavior such as the use of an eye-tracking device or motion analysis, the video recording method allowed the observer to track head movements that were purposefully aimed downwards, which is strongly suggestive of gaze aimed at the treads. The study demonstrated that the use of video recording for observations of stair use is an inexpensive and easy to implement method for assessing stairway design features that are being used in public places without appropriate research evidence.

Further studies using this empirical method would add to our knowledge of contemporary stairway designs and contribute to improving the usability and safety of stairways for

diverse users. Laboratory studies could contribute further toward this developing knowledge base. In a laboratory, more sophisticated measurement can be implemented. Moreover, different types of interaction can be studied and varied systematically. Laboratory research would not only increase our knowledge about the issues related to interactive stairway design but also be useful in testing concepts before they are implemented in public places. Other contemporary practices, such as open risers, glass stair treads, and embedded LEDs clearly require similar research attention.

4.6. Conclusion

Stair safety can be improved by understanding the impact of stairway design interventions on the rate of stair incidents. Interactive stairways were assessed by observing stair users and comparing the incidence of unsafe stair use on two interactive stairways in museum buildings with a stairway made of conventional materials in a university building. The study identified differences in the behavior of stair users (tread gaze, diverted gaze, and handrail use) between the stairways. The results indicated that interactive stairways can be as safe as any other stairway but they do alter stair use behavior. The research technique used in the study should be used to evaluate more contemporary stairway design features. An interesting finding from this work is that interactivity appears to increase vigilance while negotiating a stairway and handrail use. On the one hand, this may be a result of perceived safety risks that could otherwise be avoided. But on the other, it suggests that interactivity, in some form, can be used to increase safe behavior on stairways. The introduction of lighting at stair edges, flashing lights to bring attention to handrails, sounds that provide feedback on progress along the stairway or even as a caution to unsafe behavior, all may prove useful as countermeasures to the inherent risk of stair climbing.

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Chapter 5

5. Conclusion

5.1. Research Summary

The purpose of this thesis was to investigate contemporary practices in stairway design and the effects of stairway design features on user safety. The intent of the research was to address the knowledge gap for the design of stairways by assessing innovative design features that could cause unsafe behaviors and therefore contribute to stairway falls. While previous studies on stair incidents have mainly focused on conventional stairway designs, this research developed a low cost, easy to implement method to assess the safety of innovative stairway design features in public buildings and identify potential stairway hazards. This research demonstrated that research attention should be given to more contemporary stairway design features and that more assessments of stairways in use can help identify best practices and additional knowledge gaps.

5.2. Chapter Summaries and Results

Chapter 2 reviewed the safety of current stairway design practices as featured in *Architectural Record* over an eleven-year publication period (2000-2010) and outlined the most common stairway hazards that were found using references to U.S. building code standards and the research literature. The results demonstrated that in the professional journal, stairway design ideals and practices that were unsafe outweighed those that were safer. This suggested a need for improved professional education on safe stairway design. The chapter identified design issues that have not been addressed adequately by research which provides directions for future work on stair safety. Finally,

the chapter discussed how professional education and media could contribute to improving the attention practitioners give to stairway design.

Chapter 3 investigated the use of glass as a tread material by observing stair users and comparing the incidence of unsafe stair use on an innovative glass stairway in an Apple Retail Store with a stairway of similar configuration made of conventional materials in another retail building. The study found that the incidence rate for hesitation, misstep, and loss of balance was significantly higher in the glass stairway compared to the conventional stairway, despite also having higher rates of tread gaze and handrail use and lower rates of diverted gaze. This suggested that people experience disruptions in gait and visual attention more frequently in the Apple store than in conventional buildings. The study indicated that the glass stair tread was a contributing factor. The chapter investigated the use of glass as a flooring material in professional practice and found that there is little evidence to support this practice. The factors investigated included the absence of a universal test method for slip resistance to ensure walkway safety of all users. The chapter concluded that walking on glass treads may be more dangerous than walking on conventional treads due to reduced visibility of glass edges or reduced friction between shoes and treads.

Chapter 4 explored the use of interactive stairway features by observing stair users and comparing the incidence of unsafe stair use on two interactive stairways in museum buildings with a stairway made of conventional materials in a university building (the same methods from chapter 3). The results indicated that interactive stairways can be as safe as any other stairway but they do alter stair use behavior. The chapter discussed the impact of interactivity on stair performance and the careful consideration to application of interactive stairways in public buildings. An interesting finding from this work is that

interactivity appears to increase vigilance while negotiating a stairway and handrail use. On the one hand, this may be a result of perceived safety risks that could otherwise be avoided. But on the other, it suggested that interactivity, in some form, can be used to increase safe behavior on stairways.

5.3. Future Work

Several directions for future research have been identified in greater detail in each chapter. They include:

- Investigate the use of open risers that expose views to the surrounding environment.
- Investigate the impact of winder treads used in places where distraction cause people to turn their attention away from the stairs that are changing rapidly in size and shape.
- Investigate the use of glass as a walking surface in stairways.
- Assess the degree to which people recognize unsafe stairway design features.
- Evaluate the effectiveness of glass edges to an inattentive user's peripheral vision.
- Test the slip resistance of a variety of shoes on winding glass surfaces.
- Investigate other contemporary practices before they are used widely, such as open risers and embedded LEDs.
- Determine the level of awareness of stair safety among design professionals.
- Develop strategies to increase both public and professional awareness of stair safety.

5.4. Conclusion

Stair safety can be improved through demonstrations of the extent to which favoring aesthetics in stairway design can be dangerous. In addition, evidence supporting the effectiveness of new and innovative design approaches is needed; these studies can further our understanding of important safety issues arising from contemporary practices. Although additional research is needed to determine the correlation between innovative design features and the user's behavior in an array of environmental settings, architects and building owners have the opportunity to take responsibility for initiating safety in the design process by making intelligent use and avoiding misuses of important stairway features. The overarching goal of this thesis was to facilitate communication about safety in the design of stairways that influence safe behavior throughout the profession as an essential step toward promoting safe stairway design practices. The three main chapters (2, 3, and 4) of this thesis provided insight into the role of contemporary stairway design practices in stair safety and expanded knowledge on the use of two innovative design features, glass stair treads and interactive sound, which aims to support these conversations. It is hoped that with education and awareness on stair safety, architects and designers will take more interest in designing safer stairways that at the same time are attractive and innovative.

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